Conceptualization of System Structure as a Stepping Stone to Systems Understanding among K-12 Students

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Dedication

I dedicate this dissertation to my father, Shahin Agalarov, a legendary man who had no reproach and knew no fear.

Abstract

A new vision set forth by the *Framework for K-12 Science Education* (National Research Council, 2012) highlights the importance of developing students' abilities to think about systems as opposed to isolated facts. However, little evidence exists on how to foster students' conceptualization of systems. It has been argued that conceptualization of systems structure serves as a stepping stone to understanding of systems (Arnold & Wade, 2015; Assaraf & Orion, 2005). Thus, this dissertation presents an analysis of students' conceptualization of systems structure as a result of a curricular intervention at the high school level. The systems-oriented unit served as a context in which students' identification of connections between components within a system could be investigated. Prior research exclusively examined conceptualization of processes to understand how students develop systems understanding (Kali, Orion & Eylon, 2003; Libarkin & Kurdziel, 200). Given the stipulated relationship between systems understanding and connections between material components that make up system structure, this study investigated students' conceptualization of system structure through the ways in which they connect components within category of matter. The main objectives of the study were: 1) to examine the ways in which students identify connections between matter components within a system and use these connections as a basis for the development of a Systems Matter Framework (SMF), 2) to examine the validity of the developed framework by using this construct as a basis to evaluate students' representations of connections between system components. The evaluation of SMF validity demonstrated that this framework can be used to track growing conceptualization of system structure and to relate it with the development of systems understanding. Therefore, the SMF can be used as an instrument for student evaluation. To examine generalizability, future research needs to examine SMF in different settings.

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Chapter 1: Rationale

"*All things by immortal power […]*

to each other linked are[,]

That thou canst not stir a flower without troubling a star" (Thompson, 1897)

Some Victorian poets were greatly taken by the interconnectedness of components in the universe (MacDonald & Sertorio, 2013). In 'The Mistress of Vision', Francis Thompson (1897) identifies his unified vision of the universe by saying that "[all] things by immortal power […] to each other [are] linked". The poet is alluding to the fact that all components are interconnected and highlights those connections further by demonstrating the degree to which components are interlinked in the universe, "[…] thou canst not stir a flower without troubling a star". Thompson uses powerful imagery to imply a series of plausible links that serve to explain a highly implausible outcome—the troubling effect of a stirred flower on a distant star (MacDonald & Sertorio, 2013). The poet calls on the need to change the ways in which humans view the world and to acquire a holistic vision of the world. .

The Thompson's call for a holistic vision closely parallels the recent focus on systems as a way to improve human understanding of complex phenomena. It has been recognized that if people approach phenomena as systems, they will act in accord with long-term consequences of their actions (Sterman, 1994). This recognition suggests that complex systems can be used to help people understand the complex phenomena that surround us (Sornette, 2004) because knowledge about how systems work can inform new ways of understanding the natural world (Cabrera, Colosi & Lobdell, 2008). Indeed, scientists approach natural systems as a set of interrelated parts that interact with each other producing specific behaviors that go beyond the properties and behaviors of individual components (Jacobson, Charlson, Rodhe & Orians, 2000). Given the important role systems play in structuring scientific research, systems were included as a unifying principle in the National Science Education Standards (National Research Council [NRC], 1996). Systems were again emphasized as one of the unifying themes for understanding science in the National Research Council's *Framework for K-12 Science Education* (NRC, 2012) which led to the Next Generation Science Standards (*NGSS)* standards (NGSS; NGSS Lead States, 2013). This long history of incorporating systems in benchmarked standards reflects the importance of developing systems thinking among students in K-12 science education (Tripto, Assaraf & Amit, 2018).

In spite of the inclusion of systems within both the *NSES* and *NGSS*, systems-based approaches to teaching K-12 science remain uncommon (Jacobson & Wilensky, 2006). Science teaching traditionally has been associated with the canonical presentation of science content as isolated facts (Aikenhead, 2006). However, instructional frameworks that promote studying scientific phenomenon as systems, such as the Earth Systems approach (Assaraf & Orion, 2005; Kali, Orion & Eylon, 2003), show improvement in students' systems thinking (Assaraf & Orion, 2005; Kali et al, 2003; Tripto et al., 2018). Although researchers claim that children are natural systems thinkers (Sweeney & Sterman, 2000), educational research identifies challenge associated with the development of systems thinking among students (Sterman, 2000). To highlight the difficulty of facilitating conceptualization of systems in students, Sterman (2000) compares efforts of mediating systems understanding in learners to flying an aircraft while trying to redesign it in flight.

Research demonstrates that identification of the connections that interrelate components within a system is one of the fundamental skills associated with systems thinking (Arnold & Wade, 2015). Because conceptualization of systems starts with learning about how components fit within system structure, it becomes important to investigate how students learn to identify connections between system components.

Unfortunately, current educational scholarship lacks both empirical and theoretical understanding of how students connect components within a system (Assaraf & Orion, 2005; Barak, Sheva, Gorodetsky, & Gurion, 1999; Kali et al., 2003). To remedy this lack of educational scholarship, this dissertation developed an analytical framework based on the ways in which high school students interrelated components within and across systems. This required the development and implementation of a systems-oriented unit as a context in which students' identification of connections between components within a system could be investigated. The development of the framework fulfilled two specific research objectives.

1. To examine the ways in which students identify connections between components within a system and use these connections as a basis for the development of an analytical framework.
2. To examine the validity of the developed framework by using this construct as a basis to evaluate students' representations of connections between system components.

Overview of the Chapters

In Chapter 2, I draw a distinction between systems as a source of knowledge and systems thinking skills as a conceptual orientation informed by this knowledge. This distinction is critical to highlight the abilities necessary for the development of systems thinking skills and emphasize the need for the conceptualization of the hierarchical structure of a system as the skill required to promote systems understanding among students. Chapter 3 describes the design of the systems-oriented curricular unit used to provide a systems rich context for investigation of students' connections between components within a system. Chapter 4 provides details in the methodology and the development of the framework in the form of a publication ready paper. It contains a brief introduction and literature review followed by details of the research methodology, a summary of the curriculum implementation, and a description of development of the analytical framework based on high school students' component connections. Chapter 5 revisits the literature relating systems thinking skills to the conceptualization of systems that resulted in the development of analytical framework. This chapter also discusses implications of using this framework as an evaluation tool and an instrument for the development of systems-oriented curriculum and future research directions.

Chapter 2: Review of Relevant Literature

In this chapter, I review literature that pertains to two areas. The first area deals with the definition of systems as theoretical constructs. A system is a theoretical construct that scientists impose upon the empirical world in order to ensure organization of naturally occurring phenomena. The second area deals with systems thinking skills that science education researchers proposed for conceptualization of systems.

This review will highlight the distinction between systems as theoretical constructs to organize the natural world and systems thinking skills that students need in order to develop an understanding of systems (Cabrera, et al., 2008). Such a distinction serves two purposes: (i) it emphasizes the diversity of different approaches to understanding systems which informs systems thinking skills (Hammond, 2010) and (ii) it helps to flesh out our understanding of *how we know what we know* about systems. Therefore, drawing the distinction between systems as theoretical constructs and systems thinking skills is important to examine competencies necessary for the conceptualization of the system, which accomplishes the first objectives of this review. Conceptualization of systems starts with understanding of the arrangement of the components within a system. This literature review discusses the need to examine the ways in which students connect components to each other within a system as an opportunity of advancing their conceptualization of systems. This discussion accomplishes the final objective of this literature review.

Systems as Constructs vs Systems as Skills : Criteria for Literature Selection

I preview the discussion on systems with a brief explanation of the conflation in terms that exists in systems-related literature. Systems as theoretical constructs and systems thinking skills have often been used in systems-related literature interchangeably

(Cabrera, 2008). Part of the conflation in terms is related to the casual use of systems in everyday language; for instance, people talk about legal, prison, or health-care systems (Arnold & Wade, 2015; Checkland, 1999). The concept of systems, even in its casual use, conveys wholeness and therefore is not new; it echoes back to Aristotle: “the [system] is more than the sum of the parts, and the parts acquire certain characteristics due to their existence in the whole” (M’Pherson, 1974, p. 221-222). As theoretical constructs, systems represent knowledge of general relationships that govern the empirical world, while systems as thinking skills represent a conceptual orientation that is derived from this knowledge of systems and is organized as an inventory of skills (Arnold & Wade, 2015; Cabrera et al., 2008; Hammond, 2010; M’Pherson, 1974). I clarify the boundaries between these two terms by first reviewing literature on systems as theoretical constructs, and then defining systems thinking competencies derived from systems as a theoretical basis.

Systems as Theoretical Constructs—General Systems Theory (GST)

Organized knowledge about systems as theoretical constructs is expressed in general systems theory (Checkland, 1999; Skyttner, 2001). Therefore, it becomes important to consider the theoretical basis of general systems theory in order to help the reader understand core systems ideas that inform the conceptualization of systems thinking skills (Checkland, 1999). Bertalanffy (1969) defined general systems theory as a new discipline that includes universal models, principles, and laws that join together many splintered disciplines and apply to systems irrespective of the nature of the system. Forming systematic theoretical constructs that embody general relationships applicable to most segments of empirical world, including fields like physics, chemistry, biology, psychology, and sociology, has become the quest of general systems theory (Boulding, 1956; Skyttner, 2001).

One of the organizational schema of general systems theory is “the arrangement of […] systems […] in a hierarchy of complexity, roughly corresponding to the complexity of the [systems] of the various empirical fields” (Boulding, 1956, p. 202). Such arrangement of systems in a hierarchy of complexity provides an opportunity to organize systems based on different types of relationships between the structural components (Mingers, 1997). The idea of relationships between components is fundamental to a holistic conceptualization of systems and allows for the organization of systems according to the scale of those relationships (Mingers, 1997). Each subsequent level of a system gives rise to a different higher organization of relations that include relations from the preceding level.

The first level in the hierarchy of complexity is the level of static structure, for example, “the spatial arrangement of atoms in a crystal”, or “mapping of the earth” (Boulding, 1956, p. 202). The accurate specification of the static and spatial relationships between components in a system (mechanical, biological, and social) enables the exploration of functional and dynamic relationships (Boulding, 1956; Kast & Rozenzweig, 1972).

The second level in the hierarchy of complex systems is simple dynamic or simple equilibrium systems with predetermined, necessary motion, such as clocks or planetary systems (Boulding, 1956; Bertalanffy, 1972; Skyttner, 2001). At this level of organization, components within a system change their spatial position through time and therefore involve relations of order, in addition to spatial arrangement (Mingers, 1997).

The third level consists of systems that contain feedback loops, such as control systems or cybernetic systems. At this level, systems are viewed as feedback loops that are open to the environment and maintain a particular state even as the environment changes (Skyttner, 2001). Because these systems work through feedback loops, they are characterized by relations between components that maintain certain variables at specific levels or control the generation of specific objects (Mingers, 1997). These may be self-regulating systems, such as a thermostat or the way bodies control internal temperature, which are organized to keep essential variables within pre-specified levels (Boulding, 1956; Mingers, 1997). This new interpretation of cybernetic systems as self-regulating entities coincided with the philosophical argument that defines biological organisms as systems (Kast & Rozenzweig, 1972; Mingers, 1997).

The fourth level of the system complexity is restricted to living organisms. At this level, relations among objects are characterized by the continuous exchange of inputs and outputs with the environment. Moreover, these open systems are capable of biological reproduction. (Boulding, 1956; Mingers, 1997). As a system at a higher level of complexity, a self-producing living organism also contains the lower levels of systems hierarchical complexity including, level 1, spatial arrangement (e.g., of organs or cells); level 2, dynamics (e.g., movement of red blood cells through the blood stream over time) and level 3, feedback loops (e.g., release of insulin to regulate sugar levels). The ability to reproduce is closely related to the ability to maintain itself, which ensures survival and adaptation to a continuously changing environment and explains higher level of complexity of living systems (Bertalanffy, 1972; Mingers, 1997; Pouvreau, 2013). Although main examples of self-producing systems are living organisms, it is also possible to conceive of an abstract self-producing systems such as *Nomic*, a game that generates its own rules (Mingers, 1997). Because characteristics of biological organisms have wider applicability to abstract systems, these definitions led to the formulation of the laws of biological entities as systems and the subsequent elaboration of unifying core systems ideas that can be also applied to mechanical or social systems (Pouvreau, 2013).

Core systems ideas. Knowledge about systems was organized into a general systems theory (GST) to expose principles that span many disciplines and is accessible to the public (Zexian & Xuhui, 2010). However, many system practitioners claim that though GST contributed to the concept of system as components interacting within demarcated boundary, it failed to provide a paradigm shift on how to apply knowledge about systems while solving complex problems (Checkland, 1981; Mingers, 1997; Zexian & Xuhui, 2010). Checkland (1981, 1988, 1999) focused his attention on shifting the paradigm from systems as knowledge towards system concepts that can be applied in various fields other than science. This work led to the derivation of core systems ideas (Bertalanffy, 1969; Boulding, 1956; Checkland, 1981; M'Pherson, 1974; Nam, 2016). Core systems ideas incorporate organizational principles that can be applied across many scientific domains from physics to biology to social sciences and includes the following ideas: (i) emergent properties, which show the whole as more than the sum of the parts; (ii) layered structure or implicit hierarchy which results in multiple levels of organization within the system; (iii) ways of communicating with the environment; and (iv) methods of control (Boulding 1956; Checkland, 1999). Each of these ideas are discussed further in the following paragraphs.

Emergent properties are properties that are represented by the whole system and are recognized by an observer as belonging to the whole system rather than to individual parts or even the aggregation of parts (Boulding, 1956; Checkland, 1981). For instance, an organism, such as a cow, is comprised of group of organs that work together to perform specific bodily functions. Although lungs, airways, and respiratory muscles serve to inhale oxygen and release carbon dioxide, the observer views the cow breathing as a whole rather than as a collection of individual respiratory organs functioning separately (Boulding, 1956; Checkland, 1999). Emergence is interdependent with the next core systems idea—hierarchy (Zexian & Xuhui, 2010).

Implicit hierarchy in a system refers to a common understanding in earlier research that many systems are composed of smaller subsystems of a lower order (Boulding, 1956; Checkland, 1999; Mingers, 1997). As such, the constructs of a subsystem and a system are relative; that is each system can generally be treated as a subsystem of a larger system (Raia, 2008). While emergent properties of a breathing capacity exist at the level of an organism; within an organism there exist smaller subsystems with their own emergent properties. The respiratory system can be further subdivided into the subsystems of the lungs, the bronchi, alveoli and the gas, each with their own emergent properties. For example, the respiratory system at a minimum consists of a subsystem that involves interaction between lung alveoli and blood vessels. This interaction results in diffusion of oxygen and carbon dioxide which leads to an emerging property of gas exchange. Emergent properties exist at different levels of organization, which constitutes the core idea of layered structure within systems (Checkland, 1981).

Checkland (1981) highlights the idea of survival of a system and the closely related core systems ideas of communication and control. Systems survive in an environment that is continuously changing, therefore survival is only possible if the system has ways or processes of communicating with the environment (Boulding, 1956;

Checkland, 1999). Communication differs for animate and inanimate systems; animate systems communicate with the environment through sensory modalities, while inanimate systems process input elements of various nature (raw materials, energy, data, information).

Control, as the final core idea, also depends on the kind of system that is being considered. It may be created by humans for instance, such as rules within the university set by the administration, or it may be automatic, such as control of core body temperature in cows (Boulding, 1956; Checkland, 1999). For instance, when environmental temperatures are above the thermoneutral zone, cows increase their metabolic rate, which stimulates heat loss to maintain body temperature. Both communication and control are collectively referred to as the "Principle of Feedback "and are effectively used to readjust the system back to an equilibrium (Boulding, 1956; Checkland, 1999).

Systems Thinking Skills

Further elaboration of core systems ideas enabled the identification of skills associated with systems thinking. Although systems thinking skills are informed by core systems ideas, these skills provide conceptual tools that enable a person to think in terms of systems as opposed to isolated objects or phenomena (Arnold & Wade, 2015; Cabrera et al., 2008; Stave & Hopper, 2007; Sweeney and Sterman, 2007). It is the intent of this section to provide a history of the development of systems thinking skills and to describe taxonomies that are currently used in the broader educational community, and in K-12 science education specifically.

Many researchers from the broad educational community have specified concepts that characterize systems thinking skills (Potash & Heinbokel, 1997; Richmond, 1994;

Sweeney & Sterman, 2000). This research has resulted in many different definitions and a great number of systems thinking taxonomies, which has created confusion. Addressing this confusion, Arnold & Wade (2015) examined definitions of systems thinking skills available in broad systems education related literature. A comparison of these definitions of systems thinking skills resulted in a comprehensive review of literature on the inventory of systems thinking skills (Arnold & Wade, 2015). They compared eight recent definitions of systems thinking skills and identified several characteristics of systems thinking. This comparison generated the following reoccurring concepts: 'interconnections', 'wholes rather than parts', 'feedback loops' and 'dynamic behavior'. Based on their comparison Arnold and Wade (2015) suggested a new framework of systems thinking by specifying eight important concepts in systems thinking, primarily based on the taxonomy by Sweeney and Sterman (2000). Table 2.1 demonstrates how systems thinking taxonomy by Arnold & Wade (2015) incorporates core systems ideas presented earlier (Checkland, 1981).

Table 2.1
Correspondence between Systems Thinking Skills and Core Systems Ideas

Systems Thinking Skills by Arnold & Wade (2015)	Core Systems Ideas
Recognizing interconnections between parts of a system	🟢 🟣
Identifying and understanding feedback loops and how they impact system behavior	🟣 🔵 🟢
Understanding system structure	🟢
Differentiating stocks, flows, and variables	🟤 🟢
Understanding of nonlinear nature of stocks and flow	🟤 🟣
Understanding dynamic behavior	🟤 🟢
Understanding of a system at different scales	🟢 🟤
Reducing complexity by modeling systems conceptually	🟢 🟤 🔵 🟣

Note. 🟤=Emergent properties; 🟢= Hieararchy; 🔵= Control; 🟣=Communication (feedback)

For instance, the core systems idea of emergent properties is represented in systems thinking skills that are associated with dynamic complexity of systems. Past empirical research has demonstrated that systems thinking must focus on the conceptualization of dynamic behavior of the system (Sweeney & Sterman, 2000). Arnold & Wade (2015) used these findings to specify skills that represent core systems ideas and reflect conceptualization of dynamic behavior of a system, specifically stocks and flows, time delays and feedback. To define these concepts, let's consider them in the context of carbon dioxide in the atmosphere. Stock is the amount of carbon dioxide in the air. Stock of carbon dioxide is influenced by both emission of the carbon dioxide (flow into the stock) and the length of time carbon dioxide is stored in trees (flow out of the stock). However, as time goes by trees wither and turn back into soil carbon, which generates time delay in the emission of carbon dioxide back to the atmosphere. Time delay causes nonlinear dynamics that have been proposed to represent an added challenge in facilitating students' understanding of systems (Sweeney & Sterman, 2000). Conceptualization of the time delay associated with ecosystem processes has been proposed to add to the systems thinking skill of 'Understanding of the nonlinear nature of stock and flow'(Table 2.1), fostering a view of systems as dynamic and complex (Arnold & Wade, 2015).

Tightly related to the understanding of dynamic complexity are systems thinking skills representing core systems ideas of communication and control, which implicitly reflect Principle of Feedback (Checkland, 1981). Principle of feedback suggests that a system uses its output and feeds it back as the input. The systems thinking skill, 'Identifying and understanding feedback loops and how they impact system behavior', promotes conceptualization of indirect effects that either amplify (positive feedback) or inhibit (negative feedback) the behavior of the system (Table 2.1). The importance of feedback loops is reflected in the ability of systems to maintain homeostasis in response to perceived changes in the environment, for instance, blood glucose maintenance. Because characterization of feedback loops involves the ability to understand time delays, advanced conceptualization of feedback loops also promotes ‘Understanding of dynamic complexity’ of systems (Arnold & Wade, 2017; Sterman & Sweeney, 2000).

While the acquisition of skills specifying dynamic complexity has been defined as ‘key’ to the conceptualization of systems (Arnold & Wade, 2017), understanding of the spatial arrangement of system components is the stepping stone without which understanding of dynamic complexity is impossible (Arnold & Wade, 2015; Boulding, 1956; Checkland, 1999). To identify the conceptualization of arrangement of components within a system, Arnold & Wade (2015) added ‘Recognizing interconnections between parts of a system’ and ‘Understanding system structure’ as two distinct skills that represent critical core systems idea of hierarchy (Table 2.1). Structure is the way of organizing something. Application of this general description to system structure requires conceptualization of relative arrangement and relations of components that comprise the hierarchical organization of systems (Arnold & Wade, 2017). Systems thinkers investigate systems by examining interrelationships that connect components. It is through the investigation of these interrelationships, that systems thinkers differentiate between components that belong to the system and components that are outside of the system, conceptualizing the hierarchy of components within a system.

Because broad systems-related education research has theorized and empirically demonstrated that conceptualization of hierarchy of a system is related to advanced understanding of a system (Potash & Heinbokel, 1997; Richmond, 1994; Sweeney &

Sterman, 2000), the K-12 science educational community developed systems thinking skills that also specify layered structure of the system (Assaraf & Orion, 2005; Kali, et al., 2003; Ossimitz, 2000). Assaraf & Orion (2005) developed one of the most comprehensive taxonomies of systems thinking skills for K-12 earth science education that closely compares to Arnold and Wade's inventory of skills (Table 2.2).

Table 2.2
Comparison between Two Frameworks of Systems Thinking Skills

Systems thinking skills (Arnold & Wade, 2015)	Systems thinking skills (Assaraf & Orion, 2005)
Recognizing interconnections between parts of a system	**Identifying components and processes within the system**
Identifying and understanding feedback loops and how they impact system behavior	**Identifying relationships among the system's components**
Understanding system structure	**Organizing the system's components and processes within a framework of relationships**
Differentiating stocks, flows and variables	Making generalizations
Understanding of nonlinear relationships of stocks and flow	Identifying dynamic relationships within the system
Understanding dynamic behavior	**Understanding the hidden dimension of the system**
Understanding of a system at different scales	Understanding the cyclic nature of systems
Reducing complexity by modeling systems conceptually	Thinking temporally: retrospection and prediction

Note. **Red color** represents skills that represent system components and interconnections in both taxonomies; **green color** represents skills that represent components from different scales in both taxonomies

Given the significance of the conceptualization of the hierarchy of a system, Assaraf & Orion (2005) identified three systems thinking skills that specify investigation of the layered structure of a system, 'Identifying components and processes within the system', 'Identifying relationships among the system's components', and 'Organizing the system's components and processes within a framework of relationships' (Table 2.2). Similar to Arnold & Wade (2015), these skills specify relative arrangement of system components within systems.

Because components are arranged within a layered structure of a system that has multiple scales, accurate conceptualization of the hierarchical arrangement of components within a system is impossible without identification of components that belong to different scales (Boulding, 1956; Checkland, 1999). To account for the connections between components that belong to multiple scales, Arnold and Wade (2015) specified a distinct skill of ‘Understanding of a system at different scales’ (Table 2.2). Along the same line, in specifying conceptualization of connections between components that belong to different scales, Assaraf and Orion (2005) defined a distinct skill of ‘Understanding of hidden dimension of the system’. Identification of elements that belong to this “hidden dimension” promotes conceptualization of molecular components that are not on the surface and advances understanding of how molecular and macro constituents connect within the layered structure of a system (Arnold & Wade, 2015; Jordan, Gray, Brooks, Honwad & Hmelo-Silver, 2013; Mohan, Chen & Anderson, 2009). Therefore, an accurate conceptualization of the hierarchical arrangement of a system includes system structure with an adequate representation of interconnections between components that belong to multiple scales. In turn, recognizing the hierarchy of system structure promotes development of more complex systems thinking skills, advancing students’ conceptualization of a system (Stave & Hopper, 2007).

Because an accurate view of interconnections between elements within the system at all levels of organization is closely associated with students’ systemic awareness, the following section of this chapter discusses the need to examine the ways in which students connect system components to each other (Arnold & Wade, 2015; Barak, Sheva, Gorodetsky & Gurion, 1999). In the following section, I substitute the concept of ‘component’ or ‘element’ with the term of ‘object' to maintain consistent terminology that broadly applies to systems of any kind.

Structural Arrangement of System Objects within the Category of Matter

During the history of investigating students’ systems thinking skills, Michelene Chi developed a framework which has been used as a basis to examine how students connect constituent objects within a system (Li Chi, Slotta & Leeuw, 1994; Libarkin & Kurdziel, 2006; Nam, 2016). Chi’s original framework described three categories – *Matter*, *Processes and Mental States*–intended to highlight ontological distinctions (Chi et al., 1994). Objects within the category of matter include structural components that have a shared set of attributes such as being “storable,” “being colored,” and “having mass” (e.g. sugar, water). The category of processes has its own distinct set of attributes that describe a series of steps occurring over time and resulting in a product (e.g. photosynthesis) (Chi et al., 1994). The final category of mental states encompasses attributions that distinguish and explain phenomena in terms of desires and wants, for instance, “the animals want to”.

Educational research that has examined students’ development of systems thinking skills has largely focused on students’ conceptualization of processes (Libarkin & Kurdziel, 2006; Nam, 2016). Libarkin & Kurdziel (2006) expanded on the category of processes to mark students’ shifts as they gain advanced understanding of geological phenomena or system (see Figure 2.1). They developed three subcategories: *Proto-Process, Mixed, and Full Process.* Student statements that were categorized as *Proto-Process* showed general recognition that a process must exist to initiate changes (Libarkin & Kurdziel, 2006). For instance, students understand that fossilization occurs without identifying the specific mechanism underlying it. In contrast, student statements

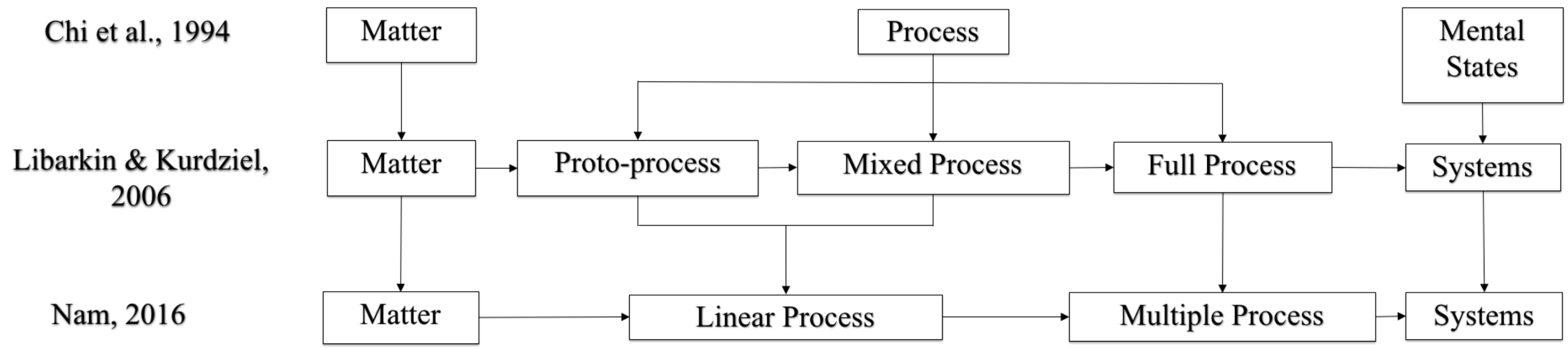


Figure 2.1. Evolution of ontological categories examining students' understanding of process

categorized as *Full Process* included a full description of the nature of the process and reflected a growing perception of Earth systems. *Full Process* statements were not necessarily correct but represented cases where students had built their own model for geologic phenomena. In this instance, students would describe fossilization as a set of processes replacing organic matter with minerals. The category of *Mixed Process* included student statements that had features of both *Proto-Process* and *Full Process* (Libarkin & Kurdziel, 2006). Nam (2016) further extended the ontological categories of processes by dividing them into linear and multiple processes to mark conceptualization of the water cycle among earth science teachers (see Figure 2.1). The *Linear Processes* category consisted of direct causal linear relations. For instance, water seepage into the ground as the result of gravity is characterized as a linear process because one mechanism (gravity) is having a singular effect. In contrast, conceptualization of *Process of Multiple Interactions* would require understanding of how a single mechanism, such as water interacting with the rock, translates into multiple physical and chemical changes (Nam, 2016).

While investigation of the processes that connect objects is essential for understanding systems, characterizing students' conceptualization of processes appears to be insufficient to appreciate how students think about systems (Assaraf, Dodick & Tripto, 2013; Kali et al., 2003). Close inspection of the ways in which students interconnect system objects within the category of matter has been predicted to advance students' understanding of the layered structure of a system and as a consequence improve students' awareness of systems (Arnold & Wade, 2017; Barak, Sheva, Gorodetsky & Gurion, 1999). However, students' conceptualization of the matter category has remained underexplored. Recognizing interconnections between matter objects within the hierarchical structure of the system advances development of systems thinking skills and conceptualization of systems among students (Arnold & Wade, 2017; Sweeney & Sterman, 2000). Thus, one of the objectives of this dissertation was to use student data to examine the ways in which they connect system objects within the category of matter and to develop a framework of object connections which is addressed in Chapter 4.

Chapter 3

Systems –Based Curricular Unit

There is a limited set of curriculum that provides systems-based approaches to science instructions (Jacobson & Wilensky, 2006). Therefore, it can be difficult to develop analytical frameworks to capture a range of students' thinking about systems. This chapter describes the curriculum that served as a context in which to examine students' conceptualization of systems. Here I provide an overview of the unit, followed by a brief review of lessons and discussion of the alignment of the curriculum with the NGSS standards (NGSS Lead States, 2013). Next, the literature on Earth Systems and the examination of biogeochemical cycles through the investigation of mechanism is discussed as the theoretical grounding for curriculum design decisions (Assaraf & Orion, 2005; Bechtel & Abrahamsen, 2008; Craver, 2013; Kali et al., 2003).

Unit Overview

The curriculum unit was developed as part of an NSF funded Water Sustainability & Climate (WSC) project (CBET – 1209402) to develop students' systems understanding of agricultural impacts on the environment. Specifically, students investigated the nitrogen cycle through the context of the negative effects of the agricultural industry on the Minnesota River Basin. The nutrient (nitrogen) rich waterways within the Minnesota River Basin flow to the Gulf of Mexico greatly affecting water quality leading to its degradation and low levels of oxygen unable to support marine life. Another, less intuitive impact of agricultural industry that students need to consider is the increased emission of greenhouse gases as a result of fertilization. Soil microbes are known to actively convert inorganic nitrogen into nitrous oxide (a potent greenhouse gas effect) and global warming heats the soil intensifying microbial processes which in turn promote the emission of greenhouse gases back into the atmosphere even further. This unit challenged students to recognize the self-reinforcing nature of two biogeochemical cycles (nitrogen and carbon), when intensification of one cycle propagates self-intensification and intensifies other cycles. Figure 3.1 shows the interaction between the two cycles within the context of agroecosystem.

The curriculum was designed to last approximately three weeks and was comprised of 15 lessons. During the unit, students engaged in the lab, hereon after referred as the chamber lab, examining nitrogen processes and discussion activities examining components and processes relevant to nitrogen cycle, such nitrification and denitrification. The unit culminated in students using software simulation to construct wetland to offset the impact of agriculture on the environment. Table 3.1 provides an overview of the lessons, accompanied by a description of lesson objectives and summary of the scientific concepts within each lesson. The table is immediately followed by a brief narrative description of each lesson.

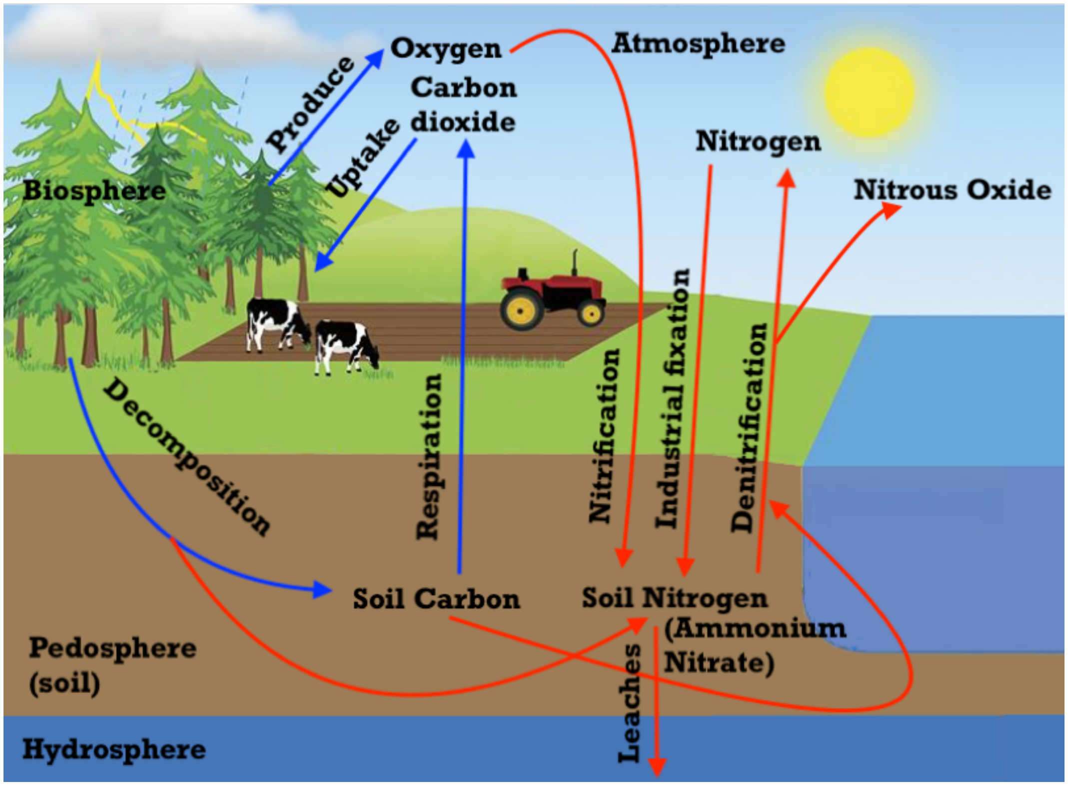


Figure 3.1. Situating processes linking nitrogen and carbon in the context of agroecosystem (blue arrows follow movement of carbon within carbon cycle; red arrows follow movement of nitrogen within nitrogen cycle across natural spheres)

Table 3.1

Sequence of Lessons with Objectives and Summary of Science

Lesson	Learning Objectives	Summary of Science
1	Students will be able to define the role of nitrogen in intensive agriculture.	Nitrogen is an important part of living cells that transforms from one form to another. The transformations that move nitrogen between the atmosphere, the land, and living things make up the nitrogen cycle. Humans have learned how to convert nitrogen from the atmosphere into nitrogen rich fertilizer, but this agricultural innovation intensifies the nitrogen cycle. As a result, there is an increased presence of nitrogen in the soil that has negatively impacted the environment.
2	Students will be able to relate nitrification lab materials to the key components of nitrification (i.e. bacteria, ammonium, nitrate, oxygen). Students will make predictions about the rate of nitrification across different soil types.	During industrial nitrogen fixation, atmospheric nitrogen is converted into ammonia, which exists in soil in the form of ammonium. During the central process of nitrification, bacteria transform ammonium (less mobile) into nitrate (more mobile) in the presence of oxygen (Fig. 3.1).
3	Students will be able to identify soil types based on bacterial count. Students will be able to explain the relationship between bacterial count and soil potential to break down glucose.	The quantity of soil bacteria present corresponds with the potential of the soil to mineralize nutrients (e.g. glucose, proteins); the higher the count of soil bacteria, the more potential the soil has to break down nutrients. Therefore, bacterial count characterizes the soil type.
4	Students will be able to explain the links connecting the following concepts: plant yield, fertilizers, carbon dioxide and components of the cellular respiration. Students will connect the micro-scale (nutrients) with macro-scale (plant yield). Students will be able to identify tillage conservation as a strategy offsetting carbon dioxide emission into the atmosphere.	Intensive fertilization increases the amount of nutrients available in the soil, which leads to an increase in plant uptake and higher plant yield. Higher plant yield results in higher plant residue and soil organic matter. Because a plant structure contains both carbon and nitrogen, soil organic matter contains both elements as well (Fig. 3.1). When this soil organic matter decomposes, part of it (glucose) is broken down in the presence of oxygen emitting carbon dioxide. Farmers can limit the emission of carbon dioxide by reducing soil tillage, which prevents oxygen from reaching the soil.
5	Students will be able to explain how nitrifying bacteria obtain energy to fix carbon. Students will be able to explain conditions required for nitrification. Students will be able to compare nitrification and photosynthesis.	Nitrification is the bacterial process that transforms ammonium into nitrate (Fig. 3.1). Nitrifying bacteria are chemoautotrophs, which draw energy from the chemical bonds of ammonium and transform it into nitrate in the presence of oxygen. Similar to photosynthetic cyanobacteria, nitrifying bacteria use derived energy to fix carbon. This comparison between photosynthetic and nitrifying bacteria highlights

		similarities and differences between processes in which they are involved.
6	Students will be able to explain how nitrification in the context of an agroecosystem contributes to high concentration of nitrates in water. Students will be able to explain how nitrates influence human health using the example of Blue Baby syndrome.	Intensive fertilization increases the amount of ammonium in soil. This ammonium is immobile and attaches itself to the soil, then it is transformed into nitrate. Because nitrate is more mobile, it easily leaches into the groundwater and builds in concentration (Fig. 3.1). High concentration of nitrates in water is harmful to biological organisms, including newborns that develop a bluish skin tint, colloquially referred to as Blue Baby syndrome.
7	Students will be able to come up with the conditions that are necessary to initiate denitrification in the lab chamber.	Denitrifying bacteria are heterotrophs, which means they need an external energy source. Similar to other heterotrophs, denitrifying bacteria draw upon the energy contained within sugar.
8	Students will be able to relate denitrification lab materials to the key components of denitrification (i.e. bacteria, nitrate, glucose). Students will be able to compare denitrification and cellular respiration. Students will make predictions on the rate of denitrification across soil types.	Denitrifying bacteria transform nitrate into nitrogen or nitrous oxide (Fig.3.1). Similar to bacteria in cellular respiration, denitrifying bacteria use energy from glucose for their growth. In contrast to bacteria in cellular respiration, denitrifying bacteria respire nitrate instead of oxygen.
9	Students will be able to explain graphic representations of the lab chamber results (nitrification and denitrification). Students will be able to explain why soil is nitrogen limited.	During the first phase of the chamber lab, nitrification, the level of nitrates in the jar gradually increases. Because nitrification is mediated by soil bacteria, the rate of this increase depends on the soil type. As bacteria uses up all the ammonium present in the jar, the nitrification stops, and the levels of nitrates stabilize. The second phase of the lab, denitrification, also mediated by soil bacteria that use external energy, is initiated by the addition of glucose. The rate of this process depends on the soil type and the amount of nitrates present in the jar. Soil ratio of carbon to nitrogen is high because soils are nitrogen limited. One of the reasons why plants cannot easily access soil nitrogen is that microbes successfully outcompete plant roots.
10	Students will be able to identify geographical location of the waterways adjacent to Blue Earth county and relate them to the Gulf of Mexico. Students will be able to explain the remote impact of high levels of nitrate on water in the Gulf of Mexico.	The school where the curriculum is implemented is located in Blue Earth county. Agriculture plays an important role in the economic growth of this area. Agricultural run-off from Blue Earth county flows into the Minnesota River Basin. Downstream, this nitrate from the Minnesota River contributes to the dead zone in the Gulf of Mexico.

11	Students will be able to relate processes investigated during the lab chamber experiment and processes occurring in wetlands. Students will be able to relate wetland activity and its impact on the environment to the processes they have examined during the lab chamber experiment.	Wetland construction is one of the land management practices used to offset the increasing concentration of nitrate in water. Though the process of denitrification lowers levels of nitrate in wetlands, it also produces nitrogen or nitrous oxide gases. Because nitrous oxide contributes to the greenhouse gas effect, wetlands can turn into a source of greenhouse gases (Fig. 3.1).
12	Students will structure a behavioral experiment that investigates one of the following predictions: 1) low-nitrogen diet increases locomotion in katydids; 2) low-nitrogen diet increases incidence of cannibalism; 3) higher locomotion results in lower cannibalism in katydids	The ratio of carbon to nitrogen exists at multiple trophic levels: soil, plants, and animals. Insects require a certain ratio of carbon to nitrogen in their diet. A shortage of nitrogen in their diet leads to changes in insect behavior. For instance, katydids have been known to demonstrate higher instances of cannibalism and locomotion when they are nitrogen deprived. To obtain enough nitrogen, katydids start cannibalizing each other. To avoid cannibalization, katydids have been hypothesized to engage in excessive locomotion.
13	Students will get familiar with biological simulation software interface and tools.	The software simulation used real-time nitrate data available from the basin of the Le Sueur watershed. The simulation allows a user to select two parameters that impact the water flow: a location and a size of a wetland. The impact of the constructed wetland is measured as nitrogen reduction.
14	Students will consider concentration of nitrates as a factor influencing the location of the constructed wetland and the rate of denitrification during simulation software activity.	As water flows across the basin, it collects nitrates. Constructed wetlands that have a central location end up collecting more water and therefore more nitrates than wetlands with marginal location. Because the rate of denitrification depends on nitrate concentration, the higher the amount of nitrates in the water, the higher the rate of denitrification. As a result, centrally constructed wetlands may result in higher reduction of nitrate levels.
15	Students will consider concentration of nitrates and water flow as they simulate construction of optimal wetlands.	The increase in water flow also limits the amount of time denitrifying bacteria has to interact with nitrates in the constructed wetlands in order to turn it into gas form, which improves water quality. Therefore, optimization of water flow needs to account for both the concentration of nitrates in the water and the amount of time bacteria spends with the nitrates in the constructed wetlands.

Narrative

The objective of the first lesson was to examine the role the nitrogen cycle plays in agroecosystems and its impact on the environment. The lesson included a teacher-led discussion on fertilization and the processes that cycle nitrogen across natural spheres. Following this discussion, students were following a prescribed set of instructions to set up the first stage of the two-phase chamber lab which examined nitrification rates for two separate soil types. The two-phase chamber lab consists of two stages, nitrification which lasts on average from 7-14 days which is followed by denitrification that lasts 2-3 days.

The objective of the second lesson was to relate components involved in the first phase of the chamber lab (nitrification) and molecular components involved in the process of nitrification. (Figure 3.2).

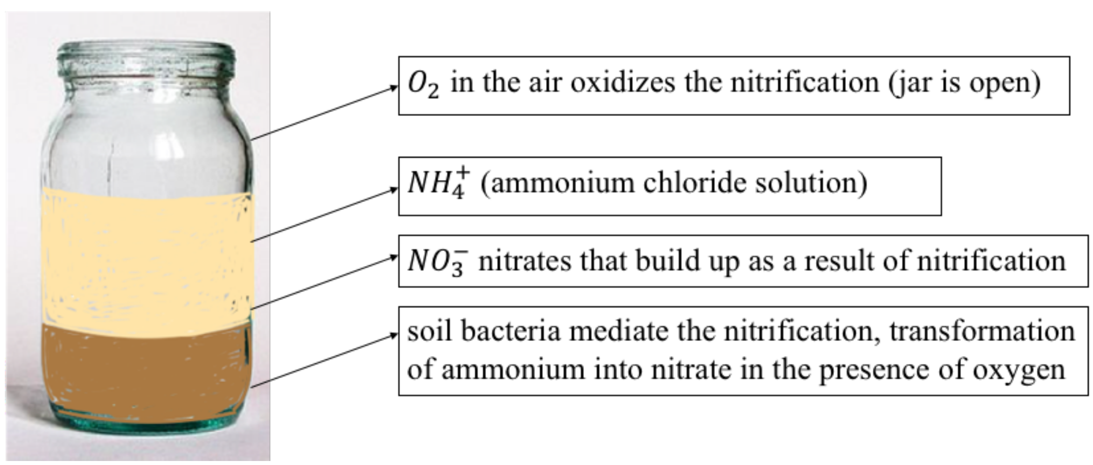


Figure 3.2. Identification of components involved in the process of nitrification

The teacher led a class discussion to help students identify the components they introduced into the lab to initiate the process of nitrification. Before taking their first nitrate measurement, students had to make written predictions on the rate of nitrification across two soil treatments that they were comparing. Students spent the rest of the class period learning how to take nitrate measurements and setting up Google spreadsheets to keep future records of nitrate measurements. For the duration of the next two weeks, students took nitrate measurements using test strips at the beginning of each class period.

The objective of the third lesson was to identify soil types based on the bacterial count and to relate the bacterial count to the bacterial activity. To provide students with evidence of the bacterial count during student-centered activity, groups of students received three images for each type of soil: backyard, compost and sand (for images see Appendix A). During student-centered activity students needed to categorize each image and support their categorization with an explanation. Students were expected to categorize images based on the number of bacteria depicted in the images.

During the next student-centered activity, groups of students were provided with two sets of two images that related bacteria count with bacterial activity as indicated by intensity of emitted carbon dioxide (see Figure 3.3). In their small group discussions, students were asked to decide which set of images correctly represented the relationship between the number of bacteria in the soil and the amount of carbon dioxide emitted into the atmosphere and to explain their decision. The teacher then led the whole class in a final discussion that ensured all students understood which set of two images represented the correct relationship between bacterial count and soil potential to break down glucose.

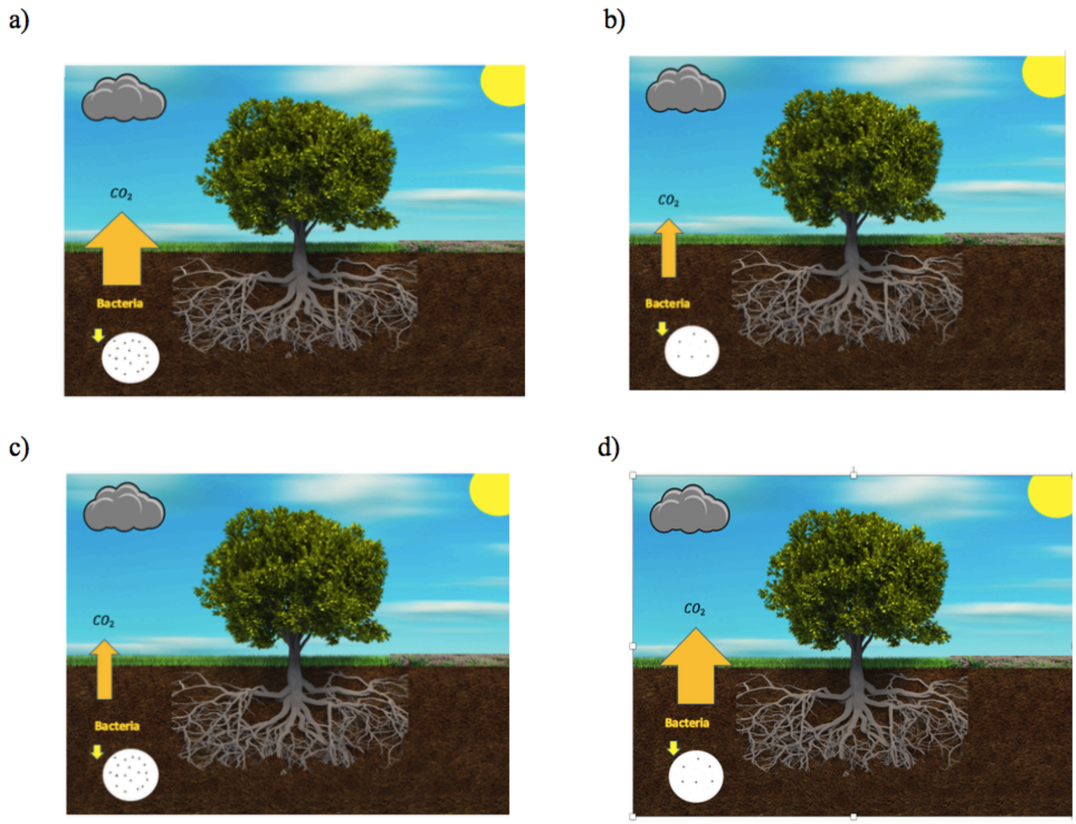


Figure 3.3. Two sets of images relating bacterial count and the rate of cellular respiration: images a) and b) represent correct relationships; images c) and d) represent incorrect relationships

The objective of the fourth lesson was to link plant growth (macro-scale) and nutrient uptake (micro-scale). The teacher reviewed previously discussed concepts by drawing arrows connecting the terms that represent a portion of an agroecosystem mapped on the whiteboard in the following order: fertilization (nutrients), plant growth, plant residue, soil organic matter, cellular respiration (formula) and two separate arrows connecting carbon dioxide to plant growth and to cellular respiration respectively (Figure 3.4).

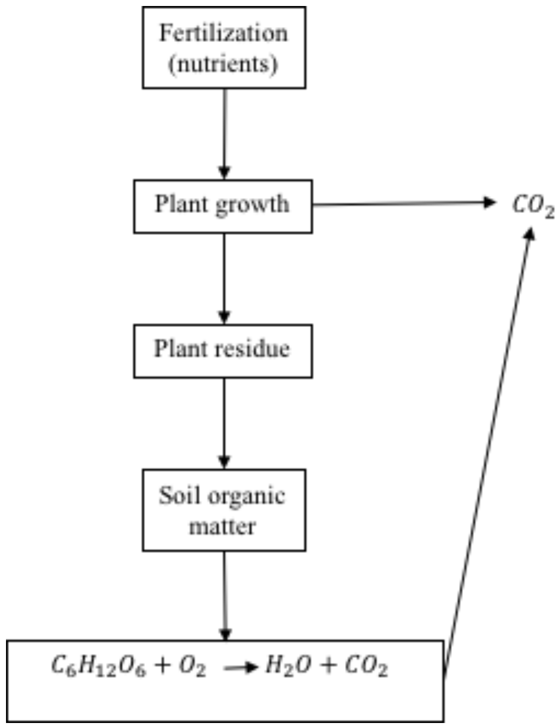


Figure 3.4. Terms representing portion of agroecosystem mapped on whiteboard

During teacher-led discussion, students were asked to predict how the relationships between these terms will change under conditions of intense fertilization (intensify or decline). For instance, students were asked to describe the impact of fertilization on plant yield, plant residue, and the uptake and emission of carbon dioxide. The teacher then led the whole class in a final discussion to ensure all students understand that the amount of carbon dioxide in the air depends on its uptake by plants and by soil emission during respiration.

The objective of the fifth lesson was to focus on the process of nitrification. During teacher-led discussion, the class examined similarities and differences between photosynthetic and nitrifying bacteria and the two processes carried out by these bacteria, photosynthesis and nitrification. During the student-centered activity that followed, students were organized into six groups to discuss the following three questions:

1) Which bacteria would have to work harder to obtain energy to fix the carbon?
2) Which bacteria would be likely to evolve earlier: chemoautotroph (nitrifying bacteria) or photoautotroph? Why? Relate your explanation to the evolution of processes.
3) Under what conditions would nitrifying bacteria have evolved earlier?

Two groups discussed each question separately, and then the groups discussing each question formed a larger group to discuss and to share their responses. Finally, students shared their responses to all the questions as a class. The teacher then led the whole class in a final discussion to highlight the differences and similarities between nitrification and photosynthesis.

The objective of the sixth lesson was to focus on how nitrification in the context of an agroecosystem contributes to the flow of matter and the presence of nitrates in water. The teacher provided students with a visual representation of a portion of an agroecosystem that included the following terms connected in the following order: fertilizer, ammonium, nitrates, plant yield, carbon dioxide (Figure 3.5).

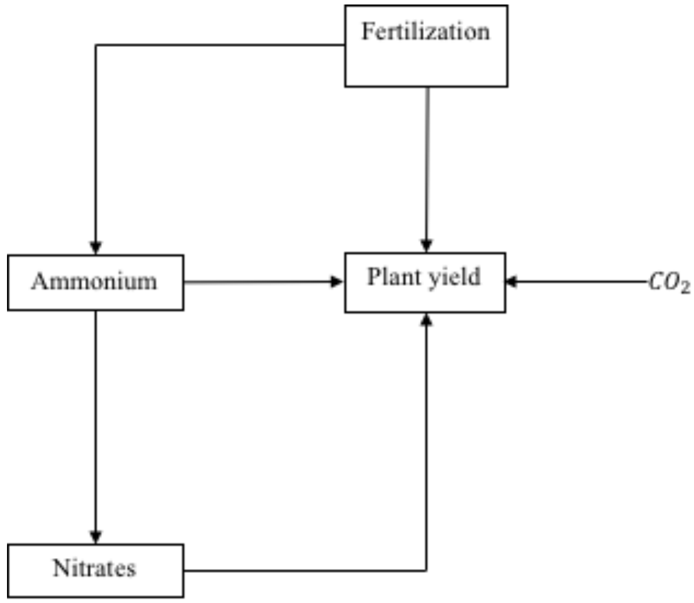


Figure 3.5. Terms representing portion of agroecosystem for student group discussion

In small groups, students discussed how each link responds under conditions of increased fertilization (intensify or decline). After a brief group discussion, the teacher led a whole class discussion verifying students' responses and explanations. The teacher then explained that excess nitrate in soil results in nitrate build up in waterways. Students spent the rest of the class reading an article on Blue Baby syndrome and responding to a set of questions in small groups. Blue Baby syndrome is a condition that can develop in babies that are fed infant formula mixed with well water if water contains high levels of nitrate. Therefore, Blue Baby syndrome serves as an example of a negative health effect of nitrate exposure. Finally, students shared the results of their group discussions with the class.

The objective of the seventh lesson was to examine conditions for denitrification and to initiate the second phase of the chamber lab, denitrification. During teacher-led class discussion, the teacher compared heterotrophic denitrifying bacteria with bacteria responsible for cellular respiration. This class discussion highlighted that heterotrophs need an external source of energy to respire nitrates or oxygen. Once conditions for denitrification were discussed, students added glucose to their jars and initiated the next stage of the chamber lab—denitrification.

The objective of the eighth lesson was to relate components involved in the second phase of the chamber lab (denitrification) and molecular components involved in the process of denitrification (Figure 3.6).

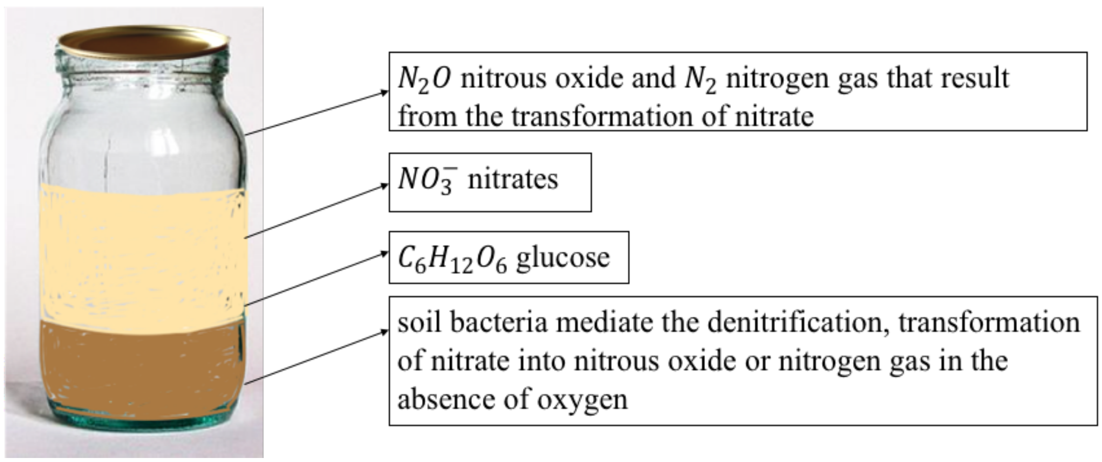


Figure 3.6. Identification of components involved in the process of denitrification

During teacher-led class discussion, students were asked questions about these molecular components and their function in the process of denitrification. During this discussion, students were asked to predict the impact of the glucose that was added to the soil in the chamber lab on the nitrate levels. Following the class discussion, students measured nitrate levels in their jars. Because nitrate levels reached zero, the chamber lab was terminated. Students joined in groups and used whiteboards to graph their results to be discussed the following day. Though students were free to choose any type of graph to visualize their data, all students used a line graph to represent their data. Figure 3.7 demonstrates graph typical for the chamber experiment.

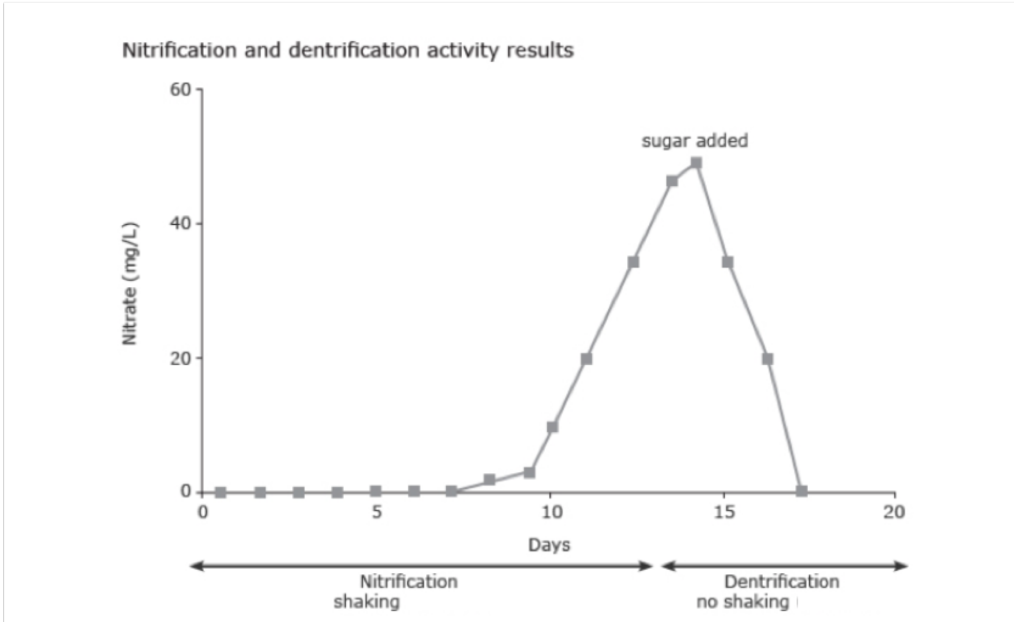


Figure 3.7. Graph demonstrating trajectory of the chamber lab experiment

The objective of the ninth lesson was to discuss how variables (soil type, concentration of ammonium, nitrate, oxygen and glucose) influenced both phases of the chamber lab as students shared their lab results. There were a total of eight questions that were distributed among students. The students worked with their groups to respond to questions that they used as a guide to analyze their graphed data. Depending on the complexity of questions, some groups of students were responsible for either two or three questions. The set of questions asked students to consider how soil type, concentration of substrates (ammonium or nitrate), oxygen and glucose influenced the slope of the graph at different points in time. After the group discussion, the teacher called on each group to share their results and to respond to additional probing questions meant to gauge student understanding.

During the final student-centered activity of the ninth lesson students were provided with a pair of images (Figure 3.8). In small groups, students had to explain how to relate bacterial count with the lower uptake of ammonium by a plant shown in picture A (Figure 3.8) versus picture B (Figure 3.8).

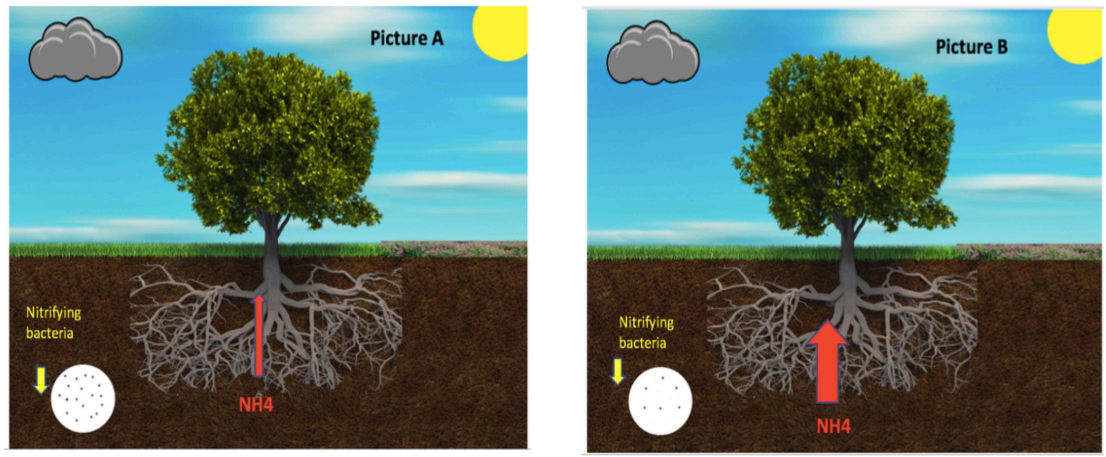


Figure 3.8. A pair of images relating microbial count and the rate of nitrification: picture A shows higher number of nitrifying bacteria that are better at competing for ammonium, than lower number of nitrifying bacteria in picture B

The objective of the tenth lesson was to relate the local impact of agricultural nitrate use on the agroecosystem with the remote impact of these nitrates on the Gulf of Mexico. The teacher introduced students to the network of waterways that connects Blue Earth county (local context) with the Gulf of Mexico. Students watched a video about the scale of the negative impact of industrial agriculture on the Gulf of Mexico, specifically a widespread hypoxia, or what is commonly referred to as dead zone. Hypoxia means low oxygen and is caused by excess nutrients, primarily nitrogen, which promotes algal overgrowth. Excessive algae growth causes high rates of decomposition, which consumes oxygen, leading to hypoxia. Students spent the rest of the class reading an article on the agricultural impacts in the Gulf of Mexico and the best land management strategies to offset these negative environmental impacts. Students were assigned to finish the article and a set of questions related to the article during the remainder of the class or as a homework.

The objective of the eleventh lesson focused on the potential positive and negative impacts of wetland construction as a pollution mitigation strategy. During the teacher-led class discussion, the teacher asked students questions about nitrification and denitrification that underlie the function of wetlands in the context of agroecosystems. The teacher used a schematic poster of a wetland to initiate a comparative discussion between wetland and the processes observed in the chamber lab (Figure 3.9). During this discussion, the teacher pointed out that wetlands absorb carbon, which benefits the atmosphere but also release greenhouse gases, such as nitrous oxide.

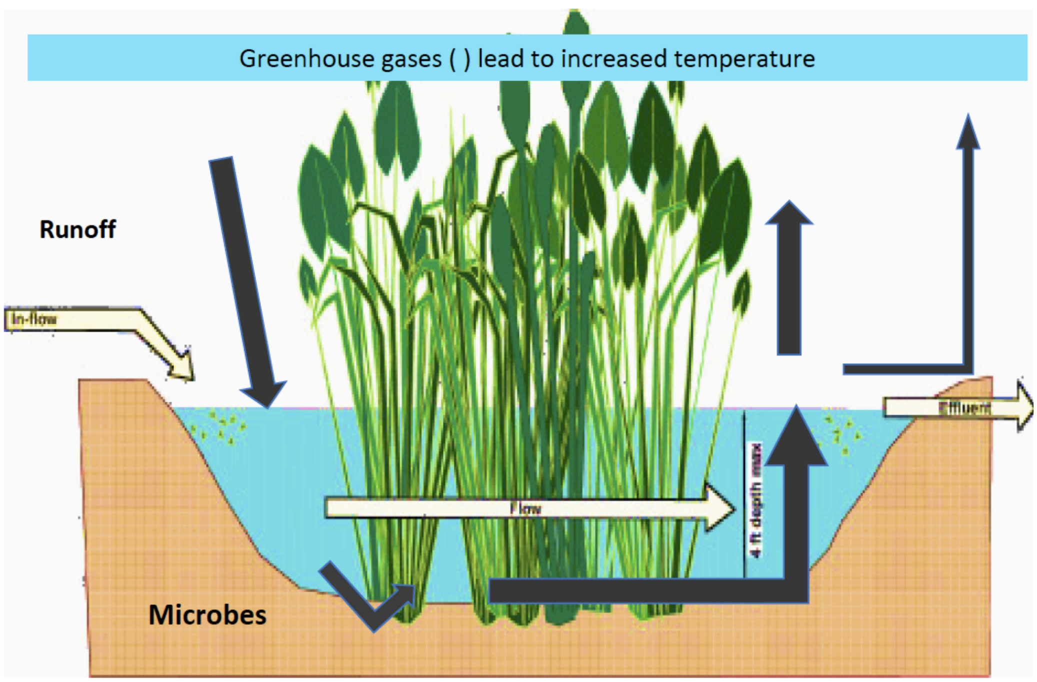


Figure 3.9. A schema of a wetland poster used during class discussion

The objective of the twelfth lesson was to highlight the carbon to nitrogen ratio at all trophic levels: soil, plants, and animals. Like plants, animals need to maintain a certain ratio of carbon to nitrogen in their cells, therefore they must consume an adequate amount of nitrogen. Some animals, specifically insects, tend to change their behavior in response to diets that are nitrogen poor. Students were divided into six groups to examine this nitrogen-dependent change in behavior in katydids. They were tasked with constructing behavioral experiments that addressed the following predictions: 1) low-nitrogen diet increases locomotion in katydids; 2) low-nitrogen diet increases incidence of katydid cannibalism; 3) higher locomotion results in lower katydid cannibalism. Two groups discussed each prediction and developed an experiment to address it, then the groups discussing each prediction formed a larger group to discuss and share their experimental designs with the rest of the class.

The objective of the thirteenth lesson was to familiarize students with the biological simulation software interface and tools. The software used is available publicly (https://maps.umn.edu/le-sueur-nitrates/). Students learned how to manipulate parameters that impact the water flow: the location and the size of the constructed wetland. Once a student learned how to manipulate these parameters, they learned how to test the impact of wetland construction, which is measured as nitrogen reduction (numerical output). At this point, students focused on the numerical output corresponding with low water flow (see Figure 3.10).

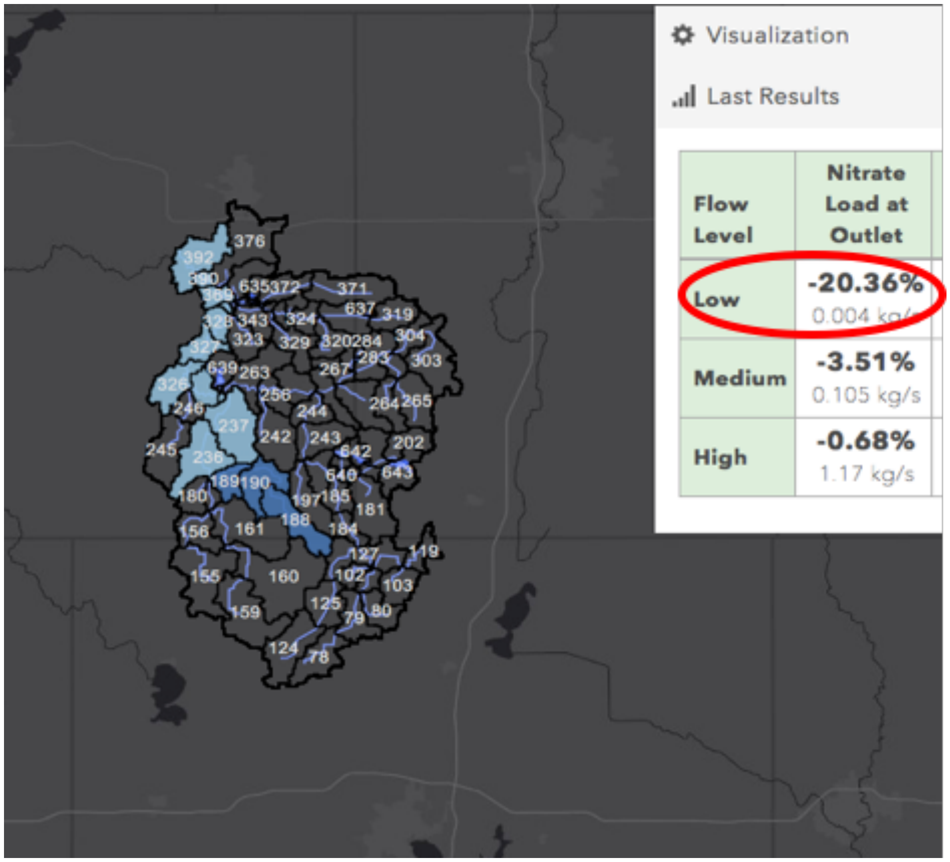
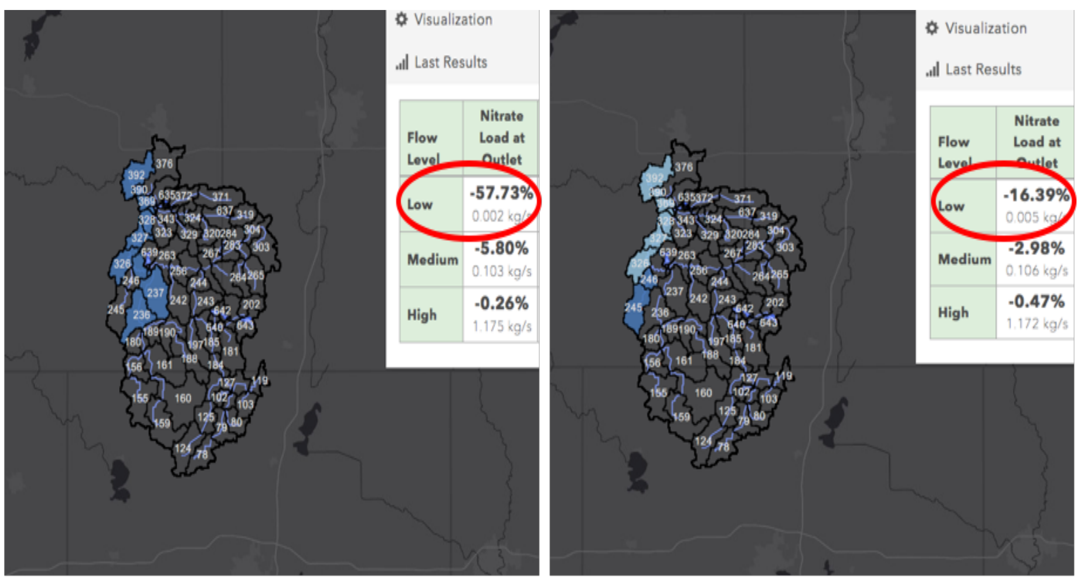


Figure 3.10. Software simulation interface demonstrates built in color gradient associated with nitrate reduction

While examining the interface of the software simulation, students learned how to interpret the color gradient associated with nitrogen reduction; the darker the color the stronger the reduction in nitrate. For instance, the reduction of nitrate immediately next to the location of wetland construction is strong and colored intensely (Figure 3.10, intense blue right next to the simulated wetland construction in the location marked as 188). However, the color and the impact of the constructed wetland fades away as we move further out from that location.

The objective of the fourteenth lesson was to highlight the concentration of nitrates as the variable that determines the rate of denitrification and efficiency of wetlands. Students practiced simulation of wetland construction both centrally (Figure 3.11a) and closer to the edge of the Le Sueur watershed (Figure 3.11b). When wetland is constructed centrally, it collects more water (run-off) and nitrates than wetlands constructed on the edge. Because denitrification (nitrate reduction) depends on the amount of nitrates in water, nitrate reduction will be higher in wetlands constructed closer to center (intense blue color in Figure 3.11a) than in wetlands constructed closer to the edge (fading out blue color gradient in Figure 3.11b).



a) b)

Figure 3.11. Construction of wetland in central sub-basin (a) results in higher nitrate reduction at the basin outlet than construction of wetland in marginal sub-basin (b)

The objective of the fifteenth lesson focused on water flow as the variable that determines the rate of denitrification and efficiency of wetlands. At this point, students' attention was directed to the numerical outputs for all levels of water flow available for each simulated construction of a wetland (Figure 3.12).

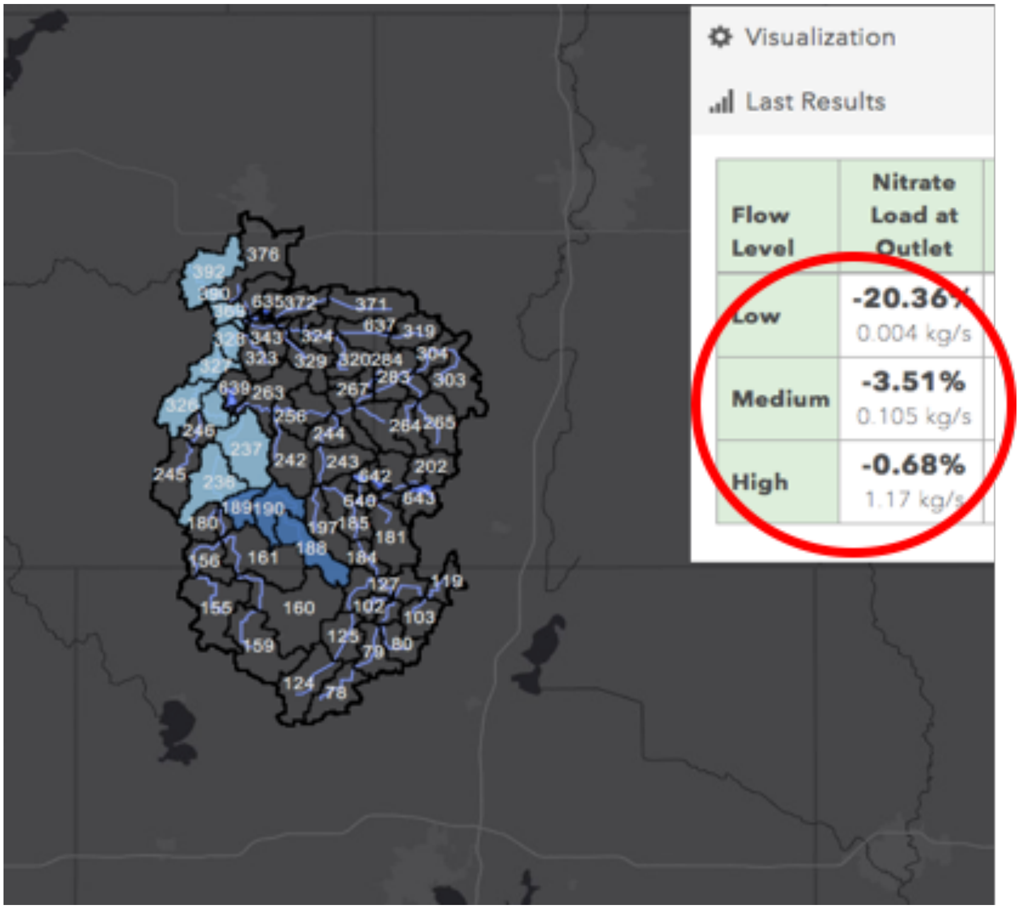


Figure 3.12. Nitrate reduction depends on the flow of water: as the water flow increases the reduction of nitrate decreases (low flow corresponds to higher absolute value than medium or high flow)

For each constructed wetland, the impact of wetland varies depending on the water flow levels. When water flow increases, denitrifying bacteria have less time to interact with nitrates, which decreases nitrate reduction. Although an increase in the amount of water increases nitrate levels, it also increases the flow of water. Therefore, to optimize their wetland construction, students considered both concentration of nitrate and amount of time bacteria interacted with nitrate when selecting their final wetland parameters.

Alignment to NGSS Standards

This section provides information about alignment between curriculum and NGSS standards integrate three dimensions: crosscutting concepts, disciplinary core ideas and scientific practices (NGSS Lead States, 2013). Cross-cutting concepts serve as a unifying theme and connect important ideas across the science disciplines providing an organizational schema for connecting content knowledge from various science fields into a scientifically based view of the world (Krajcik et al., 2014). This unit uses the cross-cutting concept of systems as its unifying theme. The *Framework for K-12 Science Education* (NRC, 2012) describes the unifying concept of systems the following way: "Defining the system under study-specifying its boundaries and making explicit a model of that system-provides tools for understanding and testing ideas that are applicable throughout science and engineering" (NRC, 2012, p.84). Embedding the idea of systems in the current curricular unit served as an opportunity to isolate a scientific phenomenon as a single system and to consider its complexity in detail.

The disciplinary core ideas (DCI) identify discipline-specific scientific principles that are relevant to the study of the particular scientific phenomena (Krajcik et al., 2014). Given the nature of the environmental issue investigated through the curricular unit, the set of activities were arranged to develop the disciplinary core ideas of Human Impact on Earth Systems, Global Climate Change, Cycle of Matter and Organization for Matter and Energy Flow in Organisms. The goal of the NGSS is to engage students in scientific and engineering practices to examine and learn the DCIs. Throughout the learning activities within the curricular unit, students engaged in scientific practices including analysis and interpretation of data, construction of explanation, designing solutions, evaluation and communication of information (see Table 3.2).

Table 3.2
Alignment between Science Topics of the Unit and Standards

Lesson (1h)	Science Topic	Disciplinary Core Ideas	Scientific and Engineering Practices
1	Nitrogen fertilization and its role in food chain	HS-ESS3-3 The sustainability of human societies and the biodiversity requires responsible management of natural resources	Asking questions and defining a problem of intensive agriculture
2	Rate of nitrification across soil treatments	HS-LS2.B Cycles of matter and energy transfer in ecosystems	Constructing explanations to support predictions on nitrification rates across experimental treatments
3	Relate microbial activity and the rate of cellular respiration	HS-LS2-3 Photosynthesis and cellular respiration (including anaerobic processes) provide most of the energy for life processes	Constructing explanations based on evidence (photo images of different soil types) for the cycling of matter and flow of energy in aerobic conditions
4	Impact of fertilization on the rate of decomposition	HS-ESS3-3 The sustainability of human societies and the biodiversity requires responsible management of natural resources HS-LS2.B Cycles of matter and energy transfer in ecosystems HS-LS2-3 Photosynthesis and cellular respiration (including anaerobic processes) provide most of the energy for life processes	Modeling matter flow activity in the context of fertilization (as a class activity)
5	Role of oxygen in nitrification	HS-LS2.B Cycles of matter and energy transfer in ecosystems HS-LS1-5 The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen	Constructing explanations to support hypothesis on evolution of nitrification and photosynthesis (temporal order)
6	Connection between human interference (fertilization) and human health (biosphere)	HS-ESS3-3 The sustainability of human societies and the biodiversity requires responsible management of natural resources	Modeling matter flow activity (as a group)

		HS-LS2-3 Photosynthesis and cellular respiration (including anaerobic processes) provide most of the energy for life processes	Constructing explanation to connect intense fertilization and decomposition which influences environment and biosphere
7	Chemo-autotrophs vs heterotrophs in the context nitrification and denitrification	HS-LS2.B Cycles of matter and energy transfer in ecosystems .	Constructing explanations on difference between energy sources autotrophic nitrifying bacteria and heterotrophic denitrifying bacteria Planning and Carrying out the second phase of the nitrogen experiment
8	Role of soil organic carbon in denitrification	HS-LS2.B Cycles of matter and energy transfer in ecosystems HS-LS1-7 Cellular respiration in which the food molecules and new compounds are formed that can transport energy to muscles.	Constructing explanations on difference between denitrification and cellular respiration
9	Multiple factors (nitrate concentration) that affect rate of nitrogen processes	HS-LS2.B Cycles of matter and energy transfer in ecosystems	Sharing data results via constructed graphs Interpreting data Constructing an explanation based on data results to analyze the influences of various factors on the rate of nitrogen processes
10	Agricultural impact on water pollution as pertinent global issue	HS-ESS3-3 The sustainability of human societies and the biodiversity requires responsible management of natural resources HS-ESS3-5 Though the magnitudes of human impacts are greater than they have ever been, so too are human abilities to model, predict, and manage current and future impacts	Asking questions and defining a problem of the negative impact of intensive agriculture on water and air quality (relate back to the experiment)
11	Relating mechanism in wetlands to lab experiment and greenhouse gas effect	HS-ESS3-3 The sustainability of human societies and the biodiversity requires responsible management of natural resources HS-ESS3-5 Though the magnitudes of human impacts are greater than they have ever been, so too are human abilities to model, predict, and manage current and future impacts	Asking questions and defining ways of offsetting the negative impact of fertilization (wetland mechanism) and relating it to the lab experiment
12	Nutrient stoichiometry (nitrogen and carbon) across trophic levels	HS-LS1-6 The sugar molecules thus formed contain carbon, hydrogen, and oxygen: their hydrocarbon backbones are used to make amino acids and other carbon-based molecules that can be assembled into	Constructing an explanation for how carbon from sugar molecule and nitrogen combine with each other to form building blocks for plant and animal cells

		larger molecules (such as proteins or DNA), used for example to form new cells	
13	Exploring software: local and remote effect of nitrogen reduction	HS-ESS3-5 Though the magnitudes of human impacts are greater than they have ever been, so too are human abilities to model, predict, and manage current and future impacts HS-ESS3-6 Through computer simulations and other studies, important discoveries are still being made about how the ocean, the atmosphere, and the biosphere interact and are modified in response to human activities	Manipulate a software simulation to illustrate possible solutions offsetting the impact of agriculture on water and the lab experiment
14	Exploring software: concentration as a limiting factor of nitrogen reduction	HS-ESS3-5 Though the magnitudes of human impacts are greater than they have ever been, so too are human abilities to model, predict, and manage current and future impacts HS-ESS3-6 Through computer simulations and other studies, important discoveries are still being made about how the ocean, the atmosphere, and the biosphere interact and are modified in response to human activities	Manipulate a software simulation to illustrate possible solutions offsetting the impact of agriculture on water and the lab experiment
15	Exploring software: water flow as a limiting factor of nitrogen reduction	HS-ESS3-5 Though the magnitudes of human impacts are greater than they have ever been, so too are human abilities to model, predict, and manage current and future impacts HS-ESS3-6 Through computer simulations and other studies, important discoveries are still being made about how the ocean, the atmosphere, and the biosphere interact and are modified in response to human activities	Manipulate a software simulation to illustrate possible solutions offsetting the impact of agriculture on water and the lab experiment

Rationale for the Systems-oriented Curricular Unit

The prior section provided an overview of the curricular unit. The following section will provide the organizational principles that guided the design of the unit. These principles are drawn from literature on Earth Systems (Assaraf & Orion, 2005; Kali et al., 2003) and mechanism (Bechtel & Abrahamsen, 2008; Craver, 2013).

Earth Systems Approach. Despite the documented advantages that K-12 students gain from a systems approach towards teaching and learning, it is largely absent from science classrooms (Jacobson & Wilensky, 2006). This absence stems from the dominating emphasis on the canonical content of science that favors teaching parts of the system in an isolated fashion rather than through consideration of the processes underlying systemic interrelationships (Hannon & Ruth, 2001). The new model of earth science education highlighted by the National Research Council (NRC) (2000b) is an attempt to apply a systems approach in earth science teaching (NRC, 2000b). A practical model for earth science education, the Earth Systems Approach, introduced by Orion (2002), focuses on biogeochemical cycles and related processes in the context of a relevant environmental issue (Assaraf & Orion, 2005; Kali et al., 2003; Mayer, 1995).

The environmental issue examined throughout the implemented curricular unit was the degrading impact of industrial agricultural practices on natural systems (Lobell & Field, 2007). One of the nutrients largely implicated in the impact of agriculture on natural systems is nitrogen. Continuous leaching of nitrogen into water systems leads to an increasing concentration of nitrate in drinking water and degradation of inland and coastal aquatic ecosystems. Increased levels of nitrogen in drinking water impairs water quality and poses real health concerns for humans and other biological organisms (Mattson et al., 1997; Ongley, 1996). Besides directly impacting biological organisms, high levels of nitrogen in large bodies of water lead to nutrient enrichment, which degrades water quality. The known consequence of nutrient enrichment is an increase in algae growth, which results in higher rates of decomposition and emission of greenhouse gases, ultimately contributing to climate change (Foley et al., 2005; Mattson et al., 1997). Thus, the impact on the environment provides an important example of an environmental issue relevant to current education reforms and a real-life context to investigate the nitrogen cycle situated at the heart of this agriculture-related issue.

Detailed examination of nitrogen processes focuses on the interaction between the nitrogen cycle and components of the carbon cycle, representing a systems view of the nitrogen cycle endorsed by scientists (Jacobson, Charlson, Rodhe & Orians, 2000). Interactions between the nitrogen and carbon cycles involves interrelationships between these cycles at the level of molecular processes, which lead to transformations responsible for the nitrogen cycling within an agroecosystem. The following section describes how the implemented curricular unit addresses close examination of nitrogen cycle via investigation of the mechanisms.

Investigation of the mechanisms underlying the environmental impact of agroecosystem. The concept of mechanism has received a great deal of attention in the philosophy of science. While there is still a lack of consensus on how to define mechanism (Nicholson, 2012), mechanisms are largely understood as collections of objects and processes "organized in such a way that they are responsible for a phenomenon" (Illari & Williamson, 2012, p.5). To examine the mechanism responsible for the behavior of a system or phenomenon, most philosophers include three core elements: delineation (identification of the phenomenon); decomposition (identification of constituents) and relevant organization (arrangement of objects and processes into a structured network). These elements served as organizational principles during the design of this unit, as described in the next section.

Delineation. Delineation requires identification of the phenomenon to be investigated (Craver & Darden, 2013). The identification of a phenomenon of interest defines the system boundaries and isolates the system under investigation from everything else. In this study, we defined the phenomenon under investigation as the agricultural impacts of fertilization on the environment (water and air).

Decomposition into the constituents. Decomposition of a phenomenon into levels links parts to whole through a nested hierarchy of mechanisms (Craver & Darden, 2013; Illari & Williamson, 2012). The mechanisms or processes of agricultural impacts on the environment operate on three levels, the macroscopic level of the environmental impacts, the level of cellular organisms (bacteria) responsible for the macroscopic changes and the level of molecular processes occurring within the bacterial organisms (Table 3.3).

Table 3.3

Identification of Levels of Processes Examined in the Curricular Unit (Adapted from Craver & Darden, 2013)

Level	Description	Example
First	Environmental/Macro	Construction of centrally located wetlands results in higher nitrate reduction in water
Second	Cellular	Greater amount of water (run-off) flowing through wetlands contains higher concentration of nitrates which support denitrification bacteria
Third	Molecular	Within the denitrification bacteria, nitrate is converted to nitrogen gas and nitrous oxide (by-product) ($NO_3^- \longrightarrow N_2O \longrightarrow N_2$)

One example of how the environmental impact of agriculture may be understood at three mechanistic levels is the effect of constructing wetlands that have central location which results in higher rate of nitrate reduction in water . These processes at the level of environmental impact comprise top level. To understand events occurring at the environmental or macro level, it is important to identify underlying processes that generate lower-level processes that lead to the higher rate of nitrate reduction in water. Wetlands constructed closer to the center of the basin end up collecting more water in the form of agricultural run-off. Because centrally located wetlands collect larger flow of agricultural run-off, central wetlands accumulate larger concentration of nitrates, which support denitrifying bacteria, which comprises the second cellular level of the mechanism. Because processes occurring at the molecular level generate processes that can be observed or measured at the environmental level, further investigation of the denitrification at the molecular level accounts for the transformation of nitrate into nitrogen gas, which results in measurable nitrate reduction in water that flows out of wetlands. Since the rate of denitrification depends on nitrate concentration in water, higher concentration of nitrate in centrally located wetlands results in higher rate of molecular denitrification which leads to higher rate of nitrate reduction. Therefore, to have high school students develop a systems understanding of the impacts on the environment within agroecosystems, they need to experience the complexity of processes at the molecular level (Table 3.3).

Relevant organization of the constituents. This last principle of examining mechanisms takes into account how objects and processes are situated in the context of a larger system—agroecosystem (Figure 3.13) (Craver & Darden, 2013). For instance, close examination of the molecular process of denitrification requires consideration of glucose, which serves as a source of energy for denitrifying bacteria. Investigation of the molecular processes of nitrification requires consideration of oxygen. Therefore, situation of nitrogen processes in the wider context of an agroecosystem necessitates a consideration of the origin of glucose and oxygen as part of the curricular unit. Since both oxygen and glucose represent products of the carbon cycle (photosynthesis) and are relevant to nitrogen processes, this curricular unit includes discussion of molecular objects that are involved in photosynthesis. Therefore, a systems view of the transition of nitrogen through multiple forms as it cycles through an agroecosystem involves careful consideration of relevant objects and processes at the intersection between nitrogen and carbon cycles (Jacobson et al., 2000).

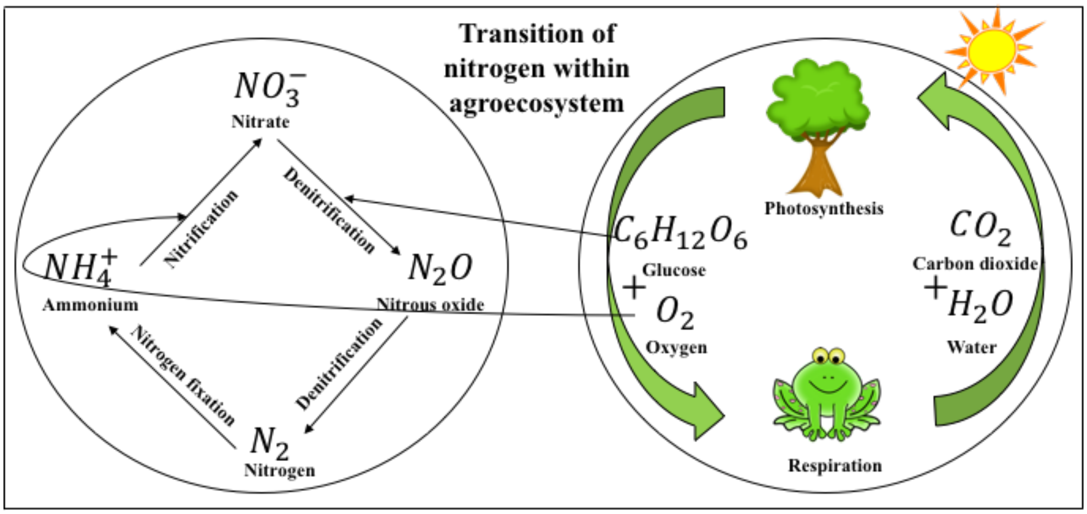


Figure 3.13. Relevant organization of objects and processes within nitrogen cycle in the context of agroecosystem

Because investigation of mechanism allows for the consideration of objects and processes relevant to the phenomenon, it facilitates the development of connections between objects that are involved. Often, these objects belong to different levels identified in Table 3.3. The following section provides a broad overview of how the investigation of mechanisms links system objects at the molecular level with the macro or environmental level.

Bridging environmental (macro) and molecular levels of mechanism. As was shown in Figure 3.1, the nitrogen cycle is a complex process which converts nitrogen from its inert atmospheric molecular form into a form that can be used by plants. The availability of nitrogen in the soil influences plant growth and ensures higher crop yield in the context of an agroecosystem. At the same time, an excessive amount of nitrogen in soil is associated with harmful impacts on the environment, such as the greenhouse gas effect and water degradation. Nitrate leaching can be toxic to biological organisms, for instance causing nitrate poisoning and blue skin coloration in newborns (Blue Baby syndrome).

Thus, the impact of soil nitrogen is not a directly proportional process where more nitrogen results exclusively in higher plant productivity. Instead, there is a complex interaction of objects that happens at the molecular level that modifies outcomes at the level of environmental impact. For example, an interaction between carbon and nitrogen cycles at the molecular level changes outcomes at the level of environmental impact: the presence of oxygen influences the rate and intensity of nitrification, which transforms the immobile form of nitrogen (ammonium) into the more mobile form of nitrogen (nitrate) that is leached as the water moves through the soil. In other words, the presence of oxygen affects the presence of mobile nitrogen forms in the soil, which influences the amount of nitrate leached into the water. Therefore, limiting the amount of oxygen that reaches the soil may reduce the rate of nitrification. To this end, a widely accepted agricultural practice is conservation of tillage, which limits the disturbance of the soil, thus limiting the amount of oxygen available for nitrification.

Use of mechanism as an organizational principle for the curriculum design allows for the consideration of objects and processes relevant to the phenomenon and facilitates the development of connections between objects that are involved. While work has been done to illuminate students' understanding of processes (Jordan, Gray, Brooks, Honwad

& Hmelo-Silver, 2013; Mohan et al., 2009), characterization of students' connections of objects within systems is underdeveloped. Using the conceptualization of systems thinking proposed by previous researchers, an analytical framework was developed based on the students' connections among objects through their engagement in the curriculum described in this chapter. The following chapter presents the developed framework in the form of a publication ready paper. As such, the paper provides a summary of the literature review and curriculum before providing details of the methodology and the development of the framework.

Chapter 4: Development of Analytical Framework Based on Shifts in Students' Representation of Connections between System Objects

There is a growing recognition that a systems-based approach is necessary to understand complex, scientific phenomena that surround us on a daily basis, such as the greenhouse gas effect (Sornette, 2004). The National Research Council's *Framework for K-12 Science Education* (NRC, 2012) supports systems as a unifying theme promoting understanding in the science classroom. Knowledge of connections between components of the system is recognized as critical in conceptualizing how systems behave (Assaraf & Orion, 2005). However, existing research lacks both empirical and theoretical understanding of how students connect components within the bounds of a system (Barak, Sheva, Gorodetsky & Gurion, 1999; Assaraf & Orion, 2005). This study focused on the development of an analytical framework to characterize how students connect system components to represent their understanding of a specific system. The framework was used to capture shifts in students' representations of these connections after students participated in a curricular unit designed to foster systems understanding.

Literature Review

Characteristics Defining Students' Systems Understanding

Systems are composed of components (hereafter objects) connected by processes, where the sum of interactions exhibits complex behavior different from the constituent parts (Chen & Stroup, 1993, Senge, 1990). The complexity of a system makes it difficult to predict future behavior of the whole system based on the individual behavior of the constituent objects (Chen & Stroup, 1993). To help students grapple with the complexity of systems, researchers argue that students need to conceptualize how system objects interrelate to each other (Assaraf & Orion, 2010; Kali, Orion & Eylon, 2003). At the beginning stage of mastering a scientific problem, students start by identifying system objects. As they progress in their understanding, students' ability to connect system objects advances, first to the ability to interrelate objects within the bounded context of a subsystem (Kali et al., 2003) and ultimately to interrelating objects across subsystems within a larger system.

The constructs of subsystem and system are relative; each system can always be treated as a subsystem of a larger system (Raia, 2008). For example, the solar system is nested within a galaxy which is nested within the universe. Since each subsystem exists relative to a larger system, object connections within a subsystem are nested within a framework of object connections within a larger system (Raia, 2008). As students expand connections between objects within a subsystem, they step outside the boundaries of the subsystem and re-examine object connections in the context of a larger system, no longer restrained by previous boundaries (Assaraf & Orion, 2005; Raia, 2008). Since conceptualization of object connections bridging separate subsystems expands the framework of object connections beyond that of a subsystem, it may serve as an indicator of advanced systems understanding (Assaraf & Orion, 2005; Kali et al., 2003).

This focus on interactions relating objects emphasizes an important aspect of many systems: objects within a system may be from different dimensions, such as macro and/or molecular. Researchers suggest that as students expand their framework of object connections, they are more likely to recognize that connected objects come from both macro and "hidden" or molecular dimensions (Assaraf & Orion, 2005; Jordan, Gray, Brooks, Honwad & Hmelo-Silver, 2013). Students who advance in their ability to connect macro and molecular dimensions use changes occurring at the molecular level to explain observable patterns of change in the system (Jordan et al., 2013; Mohan, Chen &

Anderson, 2009). In addition, students who use processes on the molecular scale to account for macro-events have been shown to reach higher levels of reasoning (Jin, Zhan & Anderson, 2013). Such empirical outcomes suggest that the ability to connect objects from macro and molecular dimensions implies higher conceptualization of complex systems (Mohan et al., 2009). This implied hierarchy suggests that conceptualization of separate dimensions may indicate development of advanced systems understanding (Assaraf & Orion, 2005; Mohan et al., 2009).

The way students conceptualize systems is affected by their knowledge of molecular processes that cycle matter through systems (Mohan et al., 2009). Assaraf & Orion (2005) established that once 8th graders connect objects in a cyclic pathway, they can connect objects from separate dimensions (macro and molecular), which advances their systems understanding. As students expand their framework of object connections within a molecular dimension, they are able to use feedback loops that interrelate objects in a less linear, more cyclic pathway (Kali et al., 2003; Mohan et al., 2009). Increased recognition of the nonlinear pathway of object connections at the molecular dimension has been closely related to students' ability to explain an emergent pattern of events consistent with higher levels of scientific explanation (Assaraf & Orion, 2005; Mohan et al., 2009). Based on these findings, Mohan theorized that nonlinear pathways of object connections may represent higher conceptualization of a system relative to linear connections between objects (Mohan et al., 2009). Combined, the results suggest that students who connect objects in nonlinear pathways show more advanced systems understanding.

In summary, the following characteristics of systems understanding have been separately proposed to be useful in examining the ways in which students connect objects within a system: (a) recognition of the relative existence of a subsystem in relation to a system; (b) distinction between molecular and macro dimensions of a system (Assaraf & Orion, 2005); (c) recognition of nonlinear pathways within each subsystem (Mohan et al., 2009). Based on students' connections between objects, this study proposes combining these characteristics into a single analytical framework which can be used to examine how students connect objects in scientific phenomena.

Past Research: Focus on Processes to Mark Students' Systems Understanding

The characterization of systems as objects connected by processes has led science education researchers to use a theory developed by Michelene Chi as a basis for analytical frameworks that examine students' understanding of systems (Li Chi, Slotta & Leeuw, 1994; Libarkin & Kurdziel, 2006; Nam, 2016). Chi's original framework describes two categories –*Matter* and *Processes* – that were proposed to track students' shifts as they advance in their conceptual understanding (Chi et al., 1994). Objects within the category of matter include structural components that have a shared set of attributes such as being "storable," "being colored," and "having mass" (e.g. sugar, water). The category of processes has its own distinct set of attributes that describe a series of steps occurring over time and resulting in a product (e.g. photosynthesis) (Chi et al., 1994).

Educational researchers expanded Chi's framework to further characterize how students understand processes as they advance in their systems understanding (Libarkin & Kurdziel, 2006; Nam, 2016). Libarkin & Kurdziel (2006) expanded on the category of processes to mark students' shifts as they gain advanced systems understanding (see Figure 1). They developed three subcategories: *Proto-Process, Mixed, and Full Process.* Student statements that were categorized as *Proto-Process* showed general recognition that a process must exist to initiate changes (Libarkin & Kurdziel, 2006). For instance, students understand that fossilization occurs without identifying specific mechanism underlying it. In contrast, student statements categorized as *Full Process* included a full description of the nature of the process and reflected a growing perception of Earth systems. In this instance, students would describe fossilization as a set of processes replacing organic matter with minerals. The category of *Mixed Process* included student statements that had features of both *Proto-Process* and *Full Process* (Libarkin & Kurdziel, 2006). Nam (2016) further extended the ontological categories of processes by dividing them into linear and multiple processes to mark conceptualization of the water cycle among earth science teachers (see Figure 4.1). The *Linear Processes* category consisted of direct causal linear relations. For instance, water seepage into the ground as the result of gravity is characterized as a linear process because one mechanism (gravity) is having a singular effect. In contrast, conceptualization of *Process of Multiple Interactions* would require understanding of how a single mechanism, such as water interaction with the rock, translates into multiple physical and chemical changes (Nam, 2016).

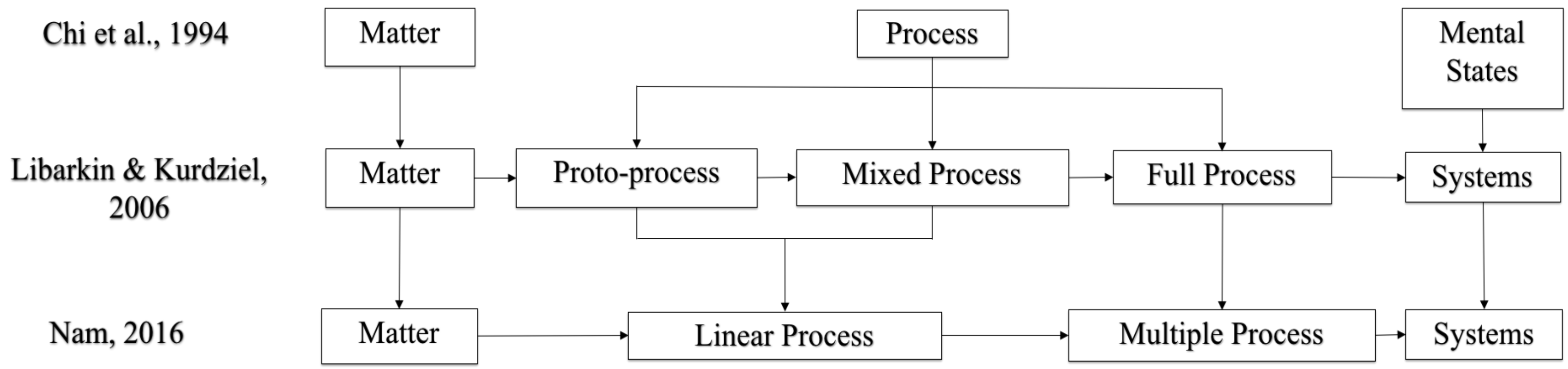


Figure 4.1 Evolution of ontological categories examining students' understanding of processes

Conceptualization of Object Connections within the Category of Matter

While investigation of processes that connect objects is essential for understanding systems, characterizing students' conceptualization of processes appears to be insufficient to appreciate how students think about systems (Assaraf, Dodick & Tripto, 2011; Kali et al., 2003). Researchers have suggested that students' ability to interrelate matter objects within a framework of connections serves as a precursor to increased systems understanding (Assaraf & Orion, 2010; Assaraf et al., 2011). Close inspection of the ways in which students connect system objects within the category of matter has been postulated to explain how those connections advance students' systems understanding (Assaraf & Orion, 2005). However, students' conceptualization of the matter category has remained underexplored (Assaraf & Orion, 2005). Thus, the first objective of this research was to use student data to develop a framework of object connections within the category of matter. The next objective was to determine the construct validity of the framework by applying this framework to students' concept maps.

Methods

Setting and Participants

Study participants were high school seniors enrolled in a single-semester elective wildlife ecology course in a large rural town in the Midwest. Twenty-one of the 31 students enrolled in the course, those with appropriate permissions and complete data sets, were included in this study. The high school serves 981 students with the following demographics: 71% Caucasian, 7% Hispanic, 4% Asian, 1% American Indian, and 16% African American.

Systems-Based Curricular Unit

The first author and the environmental science teacher (BA in biology and six years of teaching experience) designed and implemented a systems-based unit. The systems-based instructional approach focuses on the interrelationships of objects situated within a system and connected through processes (Orion, 2002). Assaraf and Orion (2005) have proposed that as students investigate processes, they learn to interrelate objects that belong to different dimensions. The Earth systems approach is a specific example of systems-based instructional methodology appropriate for the investigation of environmental issues (Assaraf & Orion, 2005; Kali et al., 2003). According to the Earth systems approach, the planet Earth functions as an integrated set of biogeochemical processes that moves chemical materials between the four spheres (geosphere, hydrosphere, atmosphere and biosphere) (Jacobson, Charlson, Rodhe & Orians, 2000; Mayer, 1995). The Earth systems approach situates interacting cycles or subsystems within the larger context of an environmental issue (Assaraf & Orion, 2005; Kali et al., 2003). The unit used in this study was situated in the context of the environmental impact of agricultural practices. Specifically, the objective was to have students engage in developing an understanding of the nitrogen cycle and its interactions with the movement of carbon in an agroecosystem. The curricular unit included 15 hours of laboratory investigations, guided-inquiry activities and a land-use computer simulation. A summary with a brief description of the lessons is provided in Table 4.1.

Table 4.1

Activities of the Unit

Lessons (1hour)	Science Topic
1	Nitrogen fertilization and its role in food chain
2	Rate of nitrification across soil treatments
3	Relate microbial activity and the rate of cellular respiration
4	Impact of fertilization on the rate of cellular respiration
5	Role of oxygen in nitrification
6	Connection between human interference (fertilization) and human health (biosphere)
7	Chemo-autotrophs vs heterotrophs in the context of nitrification and denitrification
8	Role of soil organic carbon in denitrification
9	Multiple factors (i.e. nitrate concentration) that affect rate of nitrogen processes
10	Agricultural impact on water pollution as pertinent global issue
11	Relating mechanism in wetlands to lab experiment and greenhouse gas effect
12	Nutrient stoichiometry (nitrogen and carbon) across trophic levels
13	Exploring software: local and remote effect of nitrogen reduction
14	Exploring software: concentration as a limiting factor of nitrogen reduction
15	Exploring software: water flow as a limiting factor of nitrogen reduction

Data Collection

Pre- and post-assessment data consisted of pre-structured concept maps that students completed on the first and last day of the unit (for full set of concept maps see Appendices 1B & 2B). Pre-structured concept maps represent a type of concept map that provides the student with a set of specified terms to be connected (Ruiz-Primo, Schultz, Li & Shavelson, 2000). This format restricts the number of possible terms to components the assessment provider has determined are relevant (Ruiz-Primo et al., 2000). The terms provided to students on the pre- and post-assessment maps were the same and included molecular objects within the nitrogen and carbon cycles and macro-objects shared by both cycles. Molecular objects from the carbon cycle included oxygen, carbon dioxide, and soil organic carbon; molecular objects from the nitrogen cycle included nitrite, nitrate, nitrogen, ammonium and nitrous oxide. The pre-structured concept map also contained macro-objects from the unit that served as intersections for the nitrogen and carbon cycles: plants, soil organic matter, amphibians and water. We note that although water can be perceived as a molecular object, it was treated in the unit, and by students, as a macro object.

Students were asked to connect objects using lines and to write a description of the process represented by each connected line. A word bank with descriptions of scientific processes using scientific and non-scientific terms was provided to students (for the list of description phrases see Appendix C). However, students were told that they could use other descriptions.

Data Analysis

A summary of the data analysis is provided in this section (for additional details see Appendix C, 1D & 2D). The phrases students used to describe connections between objects were examined for scientific accuracy by two experts. If two objects were appropriately connected and the connecting phrase was correct, the connection was designated as valid. Because all students made macro to macro connections, these were not considered informative for categorizing students' systems understanding and were not included as part of the analysis. Out of the 281 connections considered in this study, 221 (78.6 %) were identified as valid. These 221 valid connections were analyzed further as follows.

Valid connections were categorized by whether (i) the molecular objects were within the nitrogen or carbon cycle or between cycles and (ii) the type of objects that were connected (e.g., molecular to molecular, molecular to macro) (Table 4.2).

Table 4.2
Definitions and Examples for Connections within Nitrogen and Carbon Cycles and between Cycles

Code	Definition	Example	Proposition
Nitrogen Molecular to Nitrogen Molecular	Links between molecules from nitrogen cycle	NO_3^-—NH_4^+	nitrification
Carbon Molecular to Carbon Molecular	Links between molecules from carbon cycle	CO_2—O_2	respiration
Macro to Nitrogen Molecular	Links between nitrogen cycle molecules and macro-objects	Plant—NH_4^+	uptake
Macro to Carbon Molecular	Links between carbon cycle molecules and macro-objects	Amphibian—CO_2	release
Carbon Molecular to Nitrogen Molecular	Links connecting molecules from nitrogen and carbon cycles	O_2—NH_4^+	nitrification

To ensure inter-rater reliability during the coding process, nine pre- and nine post-concept maps were randomly selected by the primary coder. This subset of concept maps were blinded to student identity and time of assessment (pre or post) and coded by a second coder. The first author served as the primary coder, and the teacher of the unit served as the second coder. The percent concordance was 87 % (18 concept maps, 105 connections).

Development of Systems Matter Framework. By examining the ways in which valid connections were connected to one another, patterns were identified and refined through iterative discussion among the authors. While coded object connections dealt with single connections between two objects, patterns represented conceptual linking of three or more objects. These patterns formed the basis for the development of the Systems Matter Framework (SMF) (Figure 4.2). While the SMF patterns were developed from student work, they are supported by existing literature on the characteristics of systems understanding. The Systems Matter Framework combines characteristics which had previously been treated as separate into a coherent framework consisting of the following levels of categorization: i) Relative organization of object connections, ii) Multidimensional nature of object connections, and iii) Pathways of object connections.

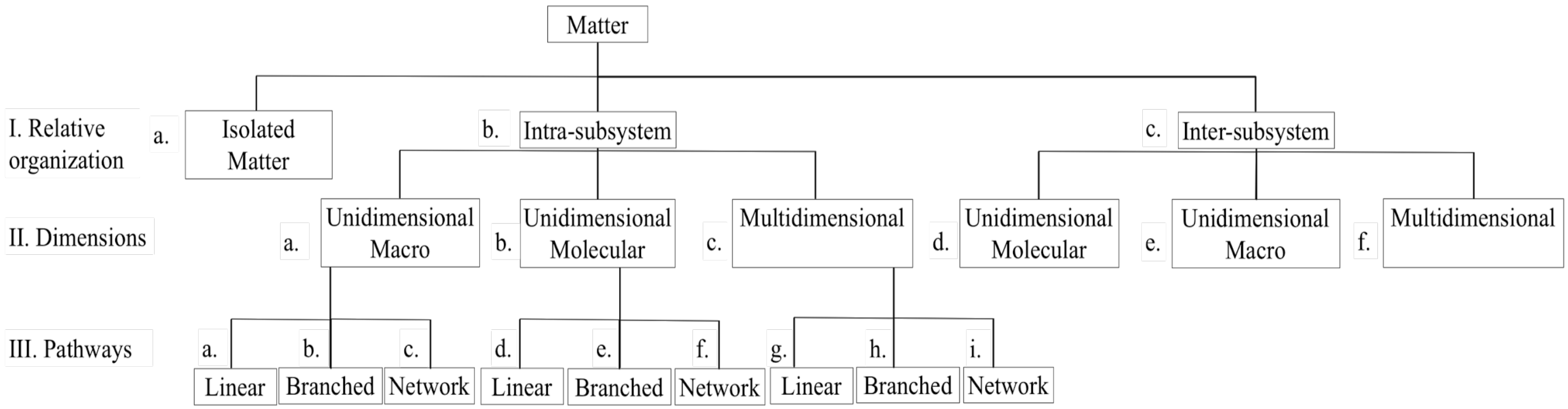


Figure 4.2. Systems Matter Framework

Relative organization of object connections. The first level of the Systems Matter Framework organizes patterns in a hierarchy from isolated objects to object connections within subsystems and between subsystems (Figure 4.2). Three broad categories of object connections were developed: Inter-subsystem, Intra-subsystem, and Isolated Matter. Patterns were first identified based on whether the student connected objects that belonged to the same cycle or to separate cycles. Patterns that only occurred within a subsystem (either the carbon or nitrogen cycle) were assigned to the Intra-subsystem category (Ib in Figure 4.2). Patterns that represented a connection across subsystems were grouped within the Inter-subsystem category (Ic in Figure 4.2). The broad category of Isolated Matter was theorized based on the notion that novice learners in lower grades (e.g. a preschooler) might assume that an object has no connection with any other objects in the phenomenon (Baillargeon, 1995).

The defining attribute of this level of categorization identifies how objects, subsystems and systems are connected in relation to each other. At this level of categorization, learners are broadly divided into those who attend to an object in isolation, as a very young learner would (Baillargeon, 1995), or a learner who perceives an object in a set of connections with other objects (Scholl, 2001). Patterns of object connections within subsystems are nested within patterns of object connections between subsystems. Therefore, the Inter-subsystem category represents an expanded pattern of object connections (Assaraf & Orion, 2005; Raia, 2008) and implies a higher level of conceptualization than the Intra-subsystem category. Since the category Isolated matter represents objects that exist outside of any connections, this construct represents the lowest level of conceptualization in the broad hierarchy of SMF taxonomy.

Multidimensional nature of object connections. The second level of categorization examined the types of objects that students connected within and across subsystems. To mark students' ability to connect dimensions, three categories were developed: Unidimensional Macro, Unidimensional Molecular and Multidimensional. These categories are subcategories of both the Intra-subsystem and Inter-subsystem categories (Figure 4.2 IIa-f). The Unidimensional category represents patterns of object connections that link objects that belong to one level of organization of matter (e.g. either molecular to molecular OR macro to macro), whereas within the Multidimensional category, patterns represent connections between two levels of organization of matter (macro to molecular). Patterns within the Intra-subsystem category where connected objects belonged to the same level (either macro or molecular) were designated as Intra-subsystem Unidimensional (IIa or IIb in Figure 4.2). For example, object connections between nitrite (NO_2^-), nitrate (NO_3^-) and nitrous oxide (N_2O) within the nitrogen cycle (Figure 4.3a) represent a pattern in the Intra-subsystem Unidimensional Molecular category (IIb in Figure 4.2). Similarly, patterns of connections that only link macro-objects—water, plant, and amphibians (Figure 4.3b)—are grouped in the Intra-subsystem Unidimensional Macro category (IIa in Figure 4.2). In contrast, the Intra-subsystem Multidimensional category contained patterns that connect macro and molecular objects within the bounds of either nitrogen (Figure 4.3c) or carbon (Figure 4.3d) subsystems (for example, plant to carbon dioxide (CO_2) and to oxygen (O_2) within the bounds of the carbon subsystem) (IIc in Figure 4.2).

A parallel categorization rationale was applied to patterns within the Inter-subsystem category. Patterns within the Inter-subsystem category where the connected objects bridging two subsystems belonged to the molecular level were classified as Inter-subsystem Unidimensional Molecular (IId in Figure 4.2). For example, object connection between a carbon subsystem molecule (soil organic carbon) and a nitrogen subsystem molecule (NO_2^-) connected subsystems (Figure 4.3e) and represented the pattern classified as Inter-subsystem Unidimensional Molecular (IId in Figure 4.2). Patterns within the Inter-subsystem category where the connection between two subsystems occurred through a macro-object (for example, plant) (Figure 4.3f) were designated as Inter-subsystem Unidimensional Macro (IIe in Figure 4.2). Patterns within the Inter-subsystem category that represented connections between subsystems simultaneously at the molecular level and through a macro-object were categorized as Inter-subsystem Multidimensional (IIf in Figure 4.2).

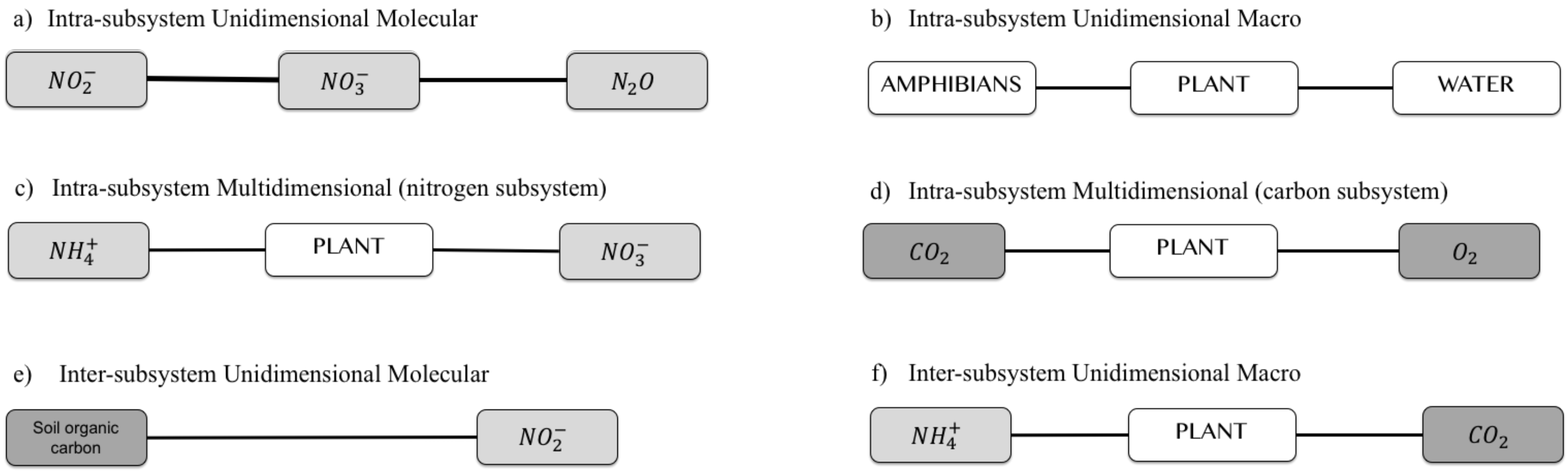


Figure 4.3. Examples of patterns in Intra-subsystem and Inter-subsystem categories: a) Intra-subsystem Unidimensional Molecular; b) Intra-subsystem Unidimensional Macro; c) Intra-subsystem Multidimensional (nitrogen subsystem); d) Intra-subsystem Multidimensional (carbon subsystem); e) Inter-subsystem Unidimensional Molecular; f) Inter-subsystem Unidimensional Macro. Key: dark shaded box-molecular objects from carbon cycle, light shaded box-molecular objects from nitrogen cycle, white color box-macroscopic objects; all molecular objects use molecular symbols or lower-case letters (soil organic carbon is considered a molecular component); all macro-objects contain upper-case letters

This second level of categorization distinguishes between macro and molecular dimensions of the system. Since the ability to connect objects from separate dimensions has been argued to be a necessary skill that advances systems understanding (Assaraf & Orion, 2005; Mohan et al., 2009), it follows that patterns reflected in the Intra-subsystem Multidimensional category represent higher conceptualization of object connections within each subsystem than patterns in the Intra-subsystem Unidimensional category. Similarly, patterns bridging subsystems through a macro-object or at the molecular level are nested within a larger framework of patterns that bridge subsystems at both macro and molecular dimensions. Therefore, resulting patterns connecting subsystems grouped within the Inter-subsystem Multidimensional category imply conceptually more sophisticated patterns than the Inter-subsystem Unidimensional Macro or Molecular categories.

Pathways of object connections. The third level of categorization examined pathways in which students connected objects within subsystems. Within the Intra-subsystem category, it was noticed that object connections were not always linear. There were three possible pathways of object connections: linear, branched and network. Linear pathways have objects connected in a straight pathway as a series of steps. The pattern of connections visualized in Figure 4.4a would be classified as the Intra-subsystem Multidimensional Linear category in SMF (IIIg in Figure 4.2). Branched pathways with objects connected in a bifurcating way, as shown in Figure 4.4b, would be classified as the Intra-subsystem Multidimensional Branched (IIIh in Figure 4.2). Finally, some network pathways have objects locked in a cycle as they connect to each other. This pathway of connections which is shown in Figure 4.4c would be classified as the Intra-Subsystem Multidimensional Network (IIIi in Figure 4.2).

Because the ability to connect objects in a cyclic pathway enhances the framework of object connections, it has been closely associated with advanced systems understanding (Assaraf & Orion, 2005; Jordan et al., 2013; Nam, 2016). Therefore, patterns grouped in Linear categories represent lower conceptualization of intra-subsystem connections than patterns in Branched and Network categories. The increasing conceptualization of pattern connections is captured by the hierarchical arrangement of Intra-subsystem categories as one moves from left to right in the Systems Matter Framework. Since the Intra-subsystem Multidimensional Network category represents patterns that connect dimensions in a cyclic pathway, it exemplifies the highest level of conceptualization within a subsystem (nitrogen or carbon).

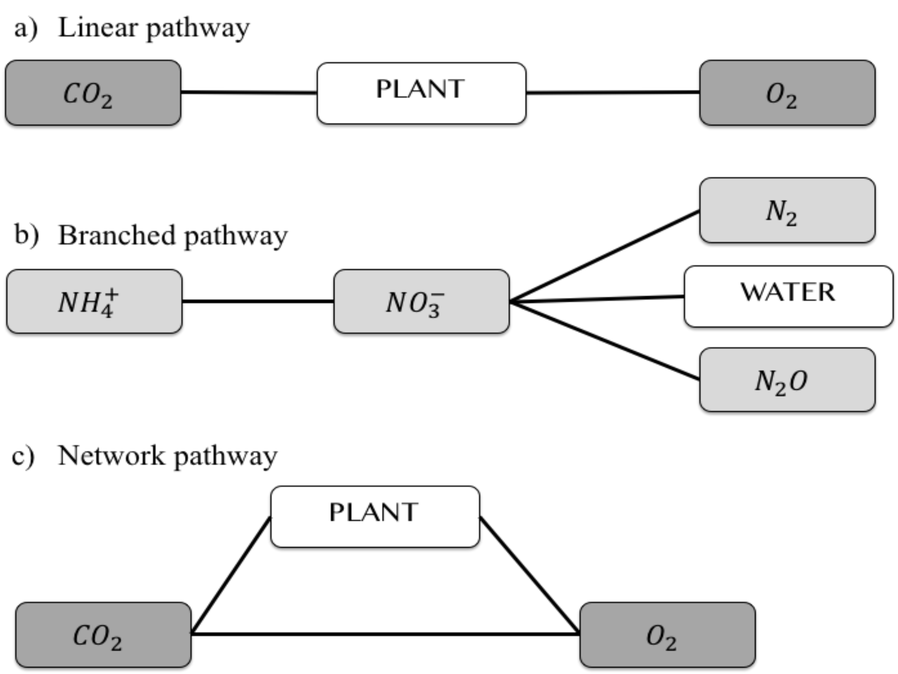


Figure 4.4. Pathways of object connections: a) Linear pathway; b) Branched pathway ; c) Network pathway; dark shade box-molecular objects from carbon cycle, light shade box-molecular objects from nitrogen cycle, white color box-macroscopic objects; all molecular objects use molecular symbols or lower-case letters (soil organic carbon is a molecular component); all macro-objects contain upper-case letters

Application and Discussion of the Systems Matter Framework

Concept Map Evaluation Procedure

The development of the Systems Matter Framework (SMF) completed the first objective of the study. The next objective was to examine how the theory encapsulated within the construct of the SMF relates to empirical research on students' concept maps (only valid connections were considered). The patterns of object connections identified within each of the 42 concept maps were evaluated for the highest generated intra-subsystem (within nitrogen and carbon subsystems separately) and inter-subsystem categories of the SMF. Examples of concept map are shown in Figure 4.5a and Figure 4.6a. Black single lines indicate connections between objects within the nitrogen subsystem. Dotted lines indicate connections between objects within the carbon subsystem. Figure 4.5b-d and Figure 4.6b highlight specific aspects of the concept maps which are addressed in the following sections. (Because concept maps were evaluated for the highest level of intra-subsystem and inter-subsystem category, object connections reflecting less sophisticated conceptualization, such as isolated matter, were not part of this analysis.)

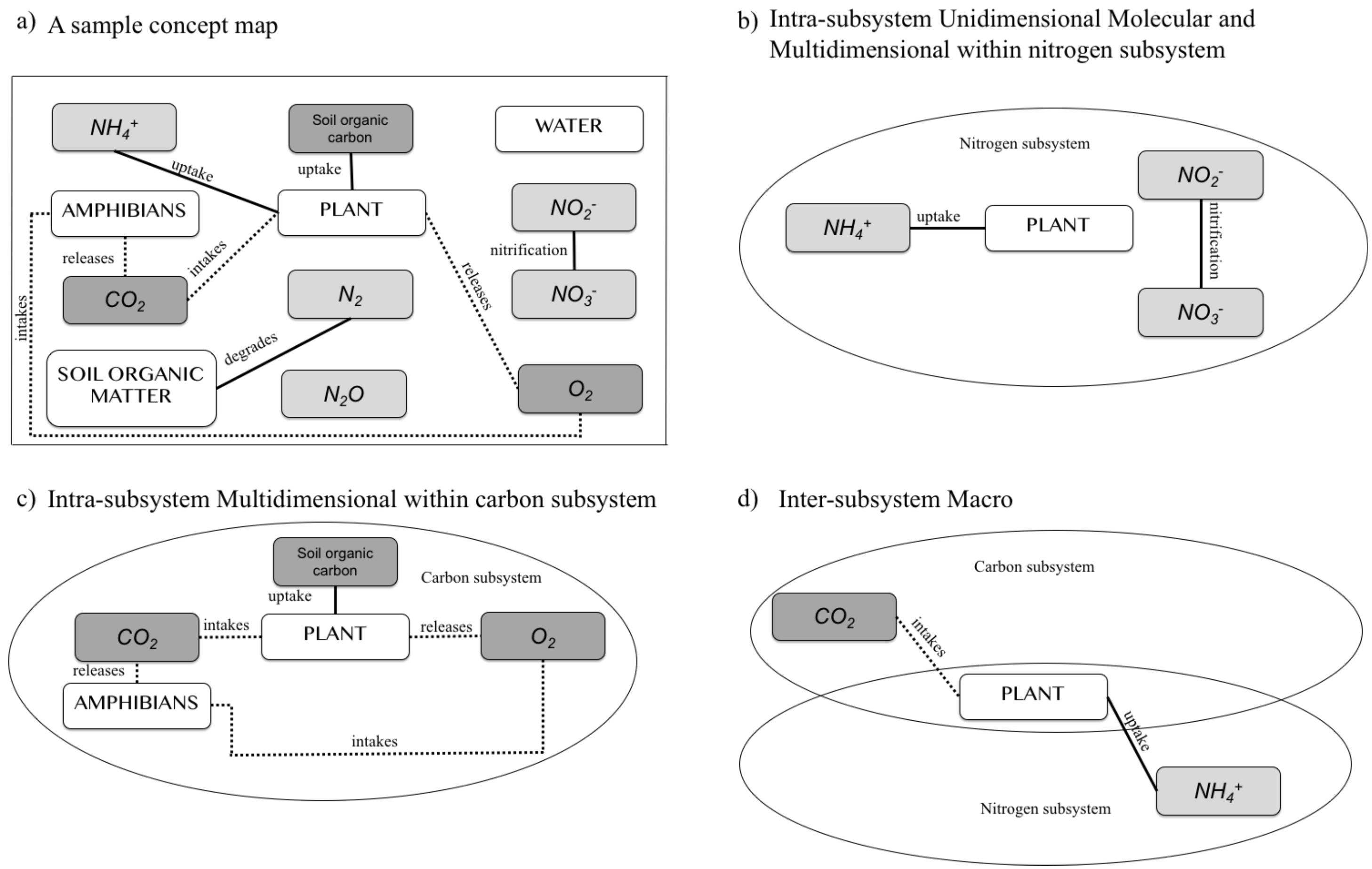


Figure 4.5. A sample concept map (a) illustrating categories: b) Intra-subsystem Unidimensional Molecular and Multidimensional within nitrogen subsystem, c) Intra-subsystem Multidimensional within carbon subsystem, d) Inter-subsystem Macro; dark shade box-molecular objects from carbon cycle, light shade box-molecular objects from nitrogen cycle, white color box-macroscopic objects; borders outlining figures b, c and d serve to feature objects that belong to each subsystem; all molecular objects use molecular symbols or lower-case letters (soil organic carbon is a molecular component); all macro-objects contain upper-case letters

Nitrogen Intra-subsystem categories. This concept map manifested more than one pattern of connections within the nitrogen subsystem (Figure 4.5b). One pattern demonstrates the connection between the ions NO_2^- and NO_3^-. Because this pattern identifies molecular objects exclusively connected to each other in a linear pathway, it is assigned to the Intra-subsystem Unidimensional Molecular Linear category (IIId in Figure 4.2). The second pattern demonstrates the connection between the macro-object of PLANT and the NH_4^+ ion. Because this pattern identifies molecular and macro objects connected to each other in a linear pathway, it is assigned to the Intra-subsystem Multidimensional Linear category (IIIg in Figure 4.2). This second pattern represents the higher conceptualization, and thus the concept map was coded as Intra-subsystem Multidimensional Linear with respect to the nitrogen subsystem.

Carbon Intra-subsystem categories. Unlike the nitrogen subsystem, this concept map manifested only one pattern of connections within the carbon subsystem. Within the carbon subsystem, macro-objects (PLANT, AMPHIBIANS) were connected to three molecular objects (carbon dioxide, oxygen, and soil organic carbon) in a network pathway (Fig. 4.5c). Therefore, this pattern was assigned to the Intra-subsystem Multidimensional Network category (IIIi in Figure 4.2), and the concept map was coded as Intra-subsystem Multidimensional Network with respect to the carbon subsystem.

Inter-subsystem categories. Patterns that included a connection across subsystems were assigned to the Inter-subsystem category. The concept map in Figure 4.5 has only one inter-subsystem pattern that is illustrated in Figure 4.5d. The black solid and dotted lines connecting molecular objects from nitrogen and carbon cycles respectively to the macro-object, PLANT, represent a pattern connecting subsystems at the macro-level. Thus, this pattern was assigned to Inter-subsystem Unidimensional Macro as the highest generated Inter-subsystem category (IIe in Figure 4.2).

Figure 4.6 further illustrates the complexity of the Inter-subsystem categories. Figure 4.6a features an example of a concept map that manifested both molecular and macro level connections between subsystems. The double line connects soil organic carbon and NO_2^- which serves to connect subsystems at the molecular level. Because there are both macro (molecular objects connected to the PLANT) and molecular level connections between the two subsystems (Fig. 4.6b), this pattern was assigned to the highest generated SMF category, Inter-subsystem Multidimensional (IIf in Figure 4.2).

a) A sample concept map illustrating Inter-subsystem Multidimensional category

b) Inter-subsystem Macro and Inter-subsystem Molecular

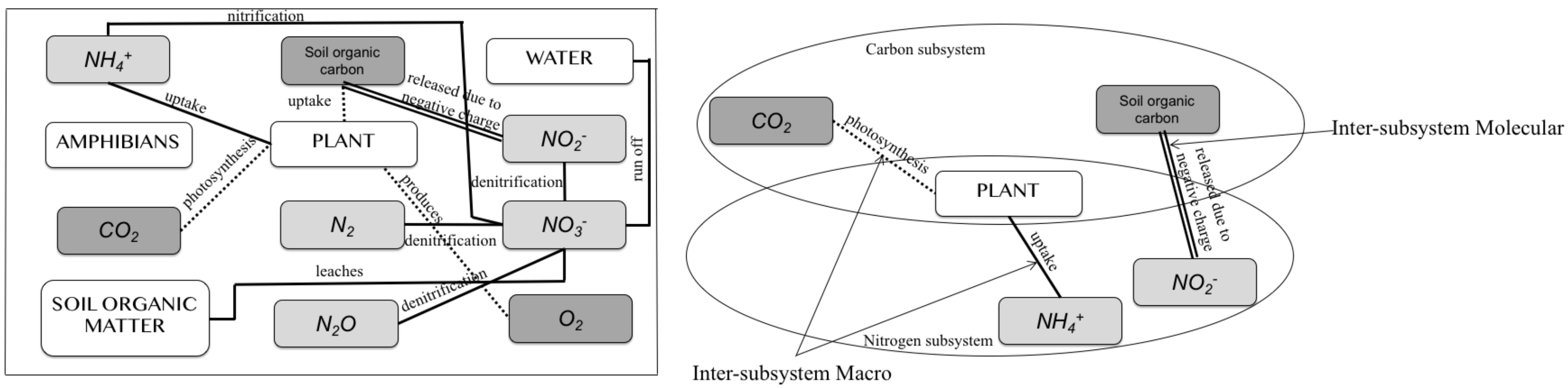


Figure 4.6. A sample concept map (a) illustrating Inter-subsystem Multidimensional category (b) which is comprised of Inter-subsystem Macro and Inter-subsystem Molecular; dark shade box-molecular objects from carbon cycle, light shade box-molecular objects from nitrogen cycle, white color box-macroscopic objects; borders outlining figure b serve to feature objects that belong to each subsystem; all molecular objects use molecular symbols or lower-case letters (soil organic carbon is a molecular component); all macro-objects contain upper-case letters

Application of the Systems Matter Framework

To examine how theory captured by the construct of a framework relates to empirical research on students' concept maps, the SMF was used to evaluate 21 pre- and 21 post-concept maps from the same students for the highest generated intra- (both carbon and nitrogen) and inter-subsystem categories. Rather than interrogation of the success of the curriculum, pre- and post-evaluation is a suitable context to apply the SMF and to examine shifts in student thinking that have been theorized to represent different patterns of object connections, captured by the SMF. Presented below are distributions of concept maps across Intra- and Inter-subsystem categories from pre- to post-assessment.

Distribution of concept maps across Inter-subsystem categories. Table 4.3 shows the categorization of concept maps for the Inter-subsystem category. The number of concept maps displaying inter-subsystem connections between the nitrogen and carbon subsystems increased from only five students in the pre-assessment to seventeen students in the post-assessment. On the pre-assessment, only one concept map displayed the highest level of systems understanding (multi-dimensional inter-subsystem category) compared to nine concept maps that showed this level of inter-subsystem connection during the post-assessment.

Table 4.3

Distribution of Concept maps across Inter-subsystem Categories from Pre- and Post-assessment

Inter-subsystem Categories	Pre-test	Post-test
Unidimensional Macro	3	6
Unidimensional Molecular	1	2
Multidimensional	1	9
Total	5/21	17/21

Distribution of concept maps across Intra-subsystem categories.

Carbon Intra-subsystem categories. Table 4.4 shows the categorization of concept maps for the Intra-subsystem category within the carbon cycle. With the exception of a single pre-concept map, all concept maps (both pre and post) were identified as Multidimensional. The highest level of categorization for the carbon intra-subsystem shifted from Linear (in the pre concept maps) to Branched and Network (in the post concept maps).

Nitrogen Intra-subsystem categories. Table 4.4 shows the categorization of concept maps for the Intra-subsystem category for the nitrogen subsystem. In contrast to the carbon subsystem, less than half of the pre-concept maps showed intra-subsystem connections for the nitrogen subsystem. At the end of the unit, most of the post-concept maps showed intra-subsystem connections for this subsystem. From pre to post, there was also a substantial shift in the number of concept maps that were categorized as Multidimensional in the post-assessment (16/21) in comparison with the pre-assessment (5/21). It is also of note that the pre-concept maps displayed exclusively linear connection categories (9/21), whereas in the post-concept maps nine of the maps were categorized as non-linear (branched or network) (9/21).

Table 4.4

Distribution of Concept Maps across Intra-subsystem Categories within Carbon and Nitrogen Subsystem from Pre- to Post-assessment

Intra-subsystem Categories	Carbon Subsystem		Nitrogen Subsystem	
	Pre-test	Post-test	Pre-test	Post-test
Unidimensional linear	0	0	4	4
Multidimensional linear	6	1	5	7
Multidimensional branched	7	13	0	4
Multidimensional network	7	7	0	5
Total	20/21	21/21	9/21	20/21

To fulfill the second objective of the study and establish the validity of the SMF construct, it becomes important to relate theory to empirical evidence based on theoretically expected relationships (Downing, 2003). Because theoretical literature stipulates that overcoming the boundedness of object connections expands the framework and advances systems understanding (Raia, 2008), students who made more connections within both subsystems were also predicted to be more likely to connect subsystems. Indeed, only students who connected objects within both subsystems were also able to connect subsystems in pre- and post-assessment (Table 4.3, 4.4). Because the ability to connect subsystems indicates advanced systems understanding (Kali et al., 2003), it became important to examine how students' ability to make inter-subsystem connections related to the way students connected objects within subsystems. As part of the validation process, the SMF was used to illustrate how changes in the Inter- and Intra-subsystem categories related to each other.

Relationship between the Intra-subsystem Multidimensional and the Inter-subsystem categories. Student data seems to support that increase in concept maps that connected dimensions within subsystems was related to an increase in concept maps that connected subsystems in post-assessment. As can be seen from Table 4.5, only five (out of 21) pre-concept maps that were categorized as Intra-subsystem Multidimensional for both the nitrogen and carbon subsystems, also connected subsystems and are therefore within the Inter-subsystem category. This correspondence became more apparent in post-assessment since higher number of post-concept maps were categorized as Intra-subsystem Multidimensional within the nitrogen and carbon subsystems simultaneously. Sixteen (out of 21) post-concept maps were assigned to the Intra-subsystem

Multidimensional categories within the nitrogen and carbon subsystems and were also assigned to the Inter-subsystem category (Table 4.5).

Consistent with theoretically and empirically based predictions (Assaraf & Orion, 2005; Kali et al., 2003), the application of the SMF construct to the students' data illustrates that students' ability to connect subsystems is closely related to their ability to connect dimensions within both subsystems. Students tended to connect dimensions within the subsystems before connecting the subsystems (Table 4.5). This relationship is particularly interesting, given that the concept map structure allowed for students to connect the subsystems without having to connect the dimensions within the subsystems. For instance, students could connect the subsystems at the molecular level by linking molecular objects from the nitrogen and carbon subsystems. These findings relate theory to the students' data and serve as an additional basis for the claim that insufficient conceptualization of dimensions hinders development of systems understanding (Assaraf & Orion, 2005; Mohan et al., 2009). Because the ability to connect subsystems has been associated with systems understanding (Assaraf & Orion, 2005; Kali et al., 2003), this correspondence would support the hierarchical, left to right, arrangement of the Intra- and the Inter-subsystem categories within the SMF.

Table 4.5

Relationship between Distribution of Concept Maps across Intra-Subsystem Multidimensional Categories and Inter-Subsystem Categories

Carbon Subsystem Multidimensional	Nitrogen Subsystem Multidimensional	Inter-Subsystem	Number of Pre-Concept Maps	Number of Post-Concept Maps
Yes	Yes	Yes	5	16
Yes	No	Yes	0	1
Yes	No	No	15	4

Note. 1 pre-concept map was excluded because it was not categorizable in intra- or inter-subsystem categories

Relationship between the Intra-subsystem Linear/Branched/Network and the Inter-subsystem categories. After exposure to the unit, nine post-concept maps were assigned to the Branched and Network categories for the nitrogen subsystem (9/21) whereas no concept maps were categorized as showing Branched and Network pathways for the nitrogen subsystem before instruction (0/21). This suggests that the implied progression shown in the SMF from linear to branched and networked pathways is valid given increased exposure to a system. Notably, all concept maps showed branched and networked pathways for the carbon subsystem both before and after exposure to the unit of instruction. This may be because the carbon subsystem is a widely studied system that students are exposed to in earlier grade levels or because the number of objects provided to students within the carbon subsystem was limited.

There is not a clear relationship, though, between connecting objects through branched and networked pathways within the nitrogen subsystem and the identification of object connections linking the subsystems. Of the seventeen concept maps that were categorized as showing inter-subsystem connections post-instruction, nine were categorized as Intra-subsystem Branched and Network and eight were categorized as Intra-subsystem Linear (Table 4.6).

These results seem to challenge theoretically and empirically established predictions that there will be correspondence between students' ability to connect objects in nonlinear pathways within the subsystems and ability to bridge the subsystems manifesting improved systems understanding. Researchers claim that as students improve in their ability to recognize cyclic or network connections between objects, they improve their systems understanding (Assaraf & Orion, 2005; Kali et al., 2003; Mohan et al., 2009). It has been proposed that because network connections among objects increases not only the quantity of connections but also the quality of connections by linking objects to each other in more scientifically meaningful pathways (Assaraf & Orion, 2005). This proposition may suggest that network connections within subsystems would closely correspond to improved systems understanding. However, small sample of students may have precluded us from being able to identify this correspondence. Additionally, the nature of the pre-structured concept maps with a limited number of objects for students to consider, may have constrained the types of pathways that students could construct.

Table 4.6
Relationship between Distribution of Concept Maps across Intra-Subsystem Nonlinear (Branched/Network) Categories and Inter-Subsystem Categories

Carbon Subsystem Branched/Network	Nitrogen Subsystem Branched/Network	Inter-Subsystem	Number of Pre-Concept Maps	Number of Post-Concept Maps
Yes	Yes	Yes	0	9
Yes	No	Yes	5	8
Yes	No	No	15	4

Note. 1 pre-concept map was excluded because it was not categorizable in intra- or inter-subsystem categories

Conclusion

This study used student data to develop and validate the Systems Matter Framework, a construct for examining students' connections of objects within systems. This construct consists of categories organized in an implied hierarchy that reflects previously theorized concepts about the development of students' ability to connect objects within systems. The three categorical levels of the SMF (Relative Organization, Dimensions, and Pathways) have been examined in isolation (Raia, 2008; Jordan et al., 2003; Assaraf & Orion, 2005; Kali et al., 2003). However, the SMF is the first framework that integrates all three characteristics into a single tool which can be used to examine object connections between matter within systems. The SMF construct incorporates two implicit hierarchies of how objects are arranged with respect to one another within a system. Moving from top to bottom, the organizational levels become more localized, starting with broad categorization of subsystems within systems, then focusing on relationships between macro and molecular dimensions of matter and finally, shifting to pathways that connect the objects within a single dimension. From left to right, the SMF reflects theoretical suppositions about the development of systems understanding from isolated matter to connecting subsystems within the Relative Organization category (Raia, 2008); from single dimensional to multidimensional connections of macro and molecular objects within the Dimensions category (Jordan et al., 2013; Mohan et al., 2009) and from linear to networked pathways within the Pathways category (Assaraf & Orion, 2005; Kali et al., 2003).

The organization of this framework implies that systems understanding develops from consideration of isolated objects within a single subsystem to the organization and connections of subsystems into a single cohesive system. This shift to inter-subsystem thinking is accompanied by shifts from unidimensional to multidimensional connections and from linear to branched or networked pathways. The initial application of this framework to student conceptualization of object connections within a system over time validated the use of the tool to track changes in systems understanding after exposure to objects and processes within a specific system. Students who interacted with a unit that focused on the objects and processes within the nitrogen subsystem shifted from object connections that were contained within single subsystems to object connections that crossed subsystems, from unidimensional to multidimensional connections and from linear to branched/networked pathways. Moreover, the predicted relationship between development of multidimensional connections of objects and connections bridging subsystems (Jordan et al., 2013; Jin et al., 2013; Mohan et al., 2009) was supported using the SMF as a tool to evaluate student connections. However, our data did not support a relationship between increased representation of branched or networked pathways and the depiction of connections between subsystems that has been predicted by others (Assaraf & Orion, 2005; Kali et al., 2003). However, because the collection of data was limited to a subset of researcher provided objects within a single system, further research and application of the SMF is needed across multiple contexts to precisely delineate these relationships.

The SMF is a much needed framework of object connections within systems which provides a current model of the development of systems understanding that can structure future research. As a framework that articulates empirically supported characteristics associated with systems understanding, the SMF can be used as a tool to track students' understanding of systems (as we have shown in a single context). Moreover, because the SMF unites these characteristics in to a single framework, it embodies theories about how systems understanding develops. Thus, the framework can not only describe but make predictions about the levers required for systems understanding. Testing of these predictions in multiple contexts can lead to insights in to how students develop systems understanding and refinement of the SMF.

Chapter 5: Discussion, Implications and Future Research

The recent push to promote understanding of systems by the National Research Council's *Framework for K-12 Science Education* (NRC, 2012) stems from the need to find ways of thinking differently about daily complexity that surrounds humans. In order to improve K-12 science teaching, the relationship between systems understanding and ways to promote conceptualization of systems must be made more explicit. Therefore, the purpose of this dissertation was to examine ways in which students interrelate objects within a system and use these interrelationships as a basis to develop a framework that can be used in secondary teaching. The objective of this chapter is to review the theoretical rationale supporting categories of Systems Matter Framework (SMF) to describe how this analytical construct can be used as an instrument for student evaluation. This review draws parallels between principles embedded in SMF and principles underlying a hierarchical arrangement of system structure, which may serve as a basis for the use of SMF as a framework for the design of systems-oriented curriculum.

Categories within SMF were based on the theoretical assumptions that students' conceptualization of system structure is progressively changing, becoming more complex and well-connected. A progressively changing conceptualization of system structure is useful in considering SMF categories as learning progressions that promote growth in connections between objects related to the system. Researchers broadly define learning progressions as the sense-making involved in conceptual understanding as newly introduced information is connected to existing knowledge shaping higher conceptualization of the system (Ausubel, Novak & Hanesian, 1968; Novak, 1980; Stevens, Delgado & Krajcik, 2010). Learning progressions predict qualitatively different levels of understanding that students advance through as they move towards higher conceptualization of systems (Novak, 1980; Stevens et al., 2010).

The SMF encapsulates different principles of understanding (Relative organization, Dimensions, Pathways) within categories suggesting that as new knowledge is consciously linked to existing concepts (objects) the learner expands their network of connections. Moving from left to right, it is proposed that as conceptualization of system structure matures, SMF categories move from connections occurring only between objects that belong to the same scale (unidimensional) to linking objects that belong to different scales (multidimensional) following progressively complex pathways of connections (Figure 4.2). Each category within unidimensional category (linear, branched and network) describes comprehensible and developmentally appropriate steps in students' progression toward more sophisticated understanding of molecular connections. Theoretical and empirical research shows that as students improve their conceptualization of molecular scale of a system, they better relate matter objects from multiple scales within a system (Ben-Zvi et al., 1986; Jordan et al., 2013; Mohan et al., 2009; Liu & Lesniak, 2005, 2006). These theoretically and empirically derived suggestions are encapsulated within the SMF categories and capture transition from molecular to multidimensional categories. After a series of learning progressions within unidimensional category and sufficient conceptualization of molecular connections, the learner can advance to the next conceptually higher category-multidimensional. This study presents evidence that students were more likely
to interrelate molecular and macro-objects after they investigated molecular complexity of agroecosystem within the unit. The predicted relationship between higher

conceptualization of the system at the molecular scale and connections bridging dimensions (Jordan et al., 2013; Jin et al., 2013; Mohan et al., 2009) was supported through the use of SMF as an evaluation tool.

It is notable that students who connected molecular objects in a branched or network pathway also linked that branch or network to macro-objects, bypassing multidimensional linear and progressing toward multidimensional branched or network categories respectively. These results available through the use of SMF as an evaluation tool provide an evidence of nonlinear progressions in student learning. Since learning is a nonlinear process (Caravita & Halden, 1994), learning progressions do not necessarily suggest a sequential series of steps towards a more sophisticated level of systems understanding (Stevens et al., 2010). According to theories of learning, students may incorporate new ideas or objects in a nonlinear fashion (Ausubel et al., 1968; Novak, 1980; Mohan et al., 2009; Stevens et al., 2010). Therefore, SMF relates conceptualization of hierarchical complexity of system structure encapsulated within categories to nonlinearity of learning progressions.

While SMF categories reflect incremental nonlinear progression, they do not imply a unidirectional route to higher conceptualization of system structure. Evaluation of concept maps through the use of the SMF as an assessment tool demonstrated that while most students showed higher conceptualization of system structure after interacting with the unit, a few students showed lower conceptualization of system structure. For example, a student who connected multiple scales in pre-assessment, linked exclusively molecular objects in a linear pathway in post-assessment, demonstrating lower conceptualization of a system. Since learning process is iterative, students may need to step back to simpler connections between objects in order to progress further in their understanding toward conceptually higher connections between objects (Stevens et al., 2010). Use of SMF as an evaluative tool provides limited evidence of the iterative nature of learning process.

Liu and Lesniak (2006) argue that students' conceptualization of systems may also develop in overlapping waves in which inconsistent views of systems may coexist. As students develop their understanding of systems, they may combine oversimplified and conceptually sophisticated connections between objects. Although we have not seen any concept maps demonstrating inconsistent connections within system structure, it was hypothesized that learners may manifest complex networks in unidimensional category and less complex linear connections in multidimensional category within the same concept map. It is possible that the small sample size limited the variation in students' representations of object connections examined in this study. Future research that involves larger sample sizes using SMF as a tool to evaluate students' systems understanding at multiple levels can reveal whether learning of systems occurs as a consistent linear progression or is better depicted as a set of overlapping waves with each level (e.g., dimension, pathways) progressing at different rates.

Implications

The SMF has strong practical implications as an analytical tool allowing teachers to provide focused feedback on student concept maps. As an alternative form of open-ended assessment, concept maps offer "more potential for uncovering knowledge integration than [close-ended] standardized tests" (Besterfield-Sacre, Gerchak, Lyons, Shuman & Wolfe, 2004). Similar to other forms of open-ended assessment, concept maps are hard to measure with high accuracy (Jonsson & Svingby, 2007). Low accuracy associated with the evaluation of concept maps precludes teachers from using them as a form of assessment despite the predicted benefits. The SMF can serve as a tool that will specify evaluation criteria and, as a consequence, facilitate instructors' feedback. The use of the SMF in combination with concept maps has the potential to motivate further use of open-ended assessments by instructors in science teaching.

The use of the SMF could promote improvements in the quality of teaching. Besides serving a purpose of evaluating students' concept maps, the SMF can be used to gain formative feedback for instructional improvement. The use of the SMF to rate student work will enable an instructor to locate the areas of weakness in students' conceptualization of systems structure and thereby identify needed improvements in the instruction. If concept mapping were done at multiple time points and teachers evaluated the work products with the SMF, they would be able to decide which individual learning activity better promotes advanced conceptualization of object connections within a system. The hierarchical arrangement of the SMF will allow instructors to categorize a learning activity to see which level of systems is being targeted (Relative Organization, Dimensions, Pathways). The formative assessments will permit the instructor to assess whether the learning activity promotes the abilities it was intended to mediate and to modify this activity accordingly.

Because the SMF framework visualizes learning progressions of students' conceptualization of system structure, it has additional implications for curriculum designers. As a framework for curriculum design, the hierarchical organization of SMF provides specific guidelines on which systems-based tasks to develop and how to arrange these tasks so that students move from less sophisticated to more sophisticated systems understanding. Because conceptualization of hierarchy advances understanding of system structure (Arnold & Wade, 2015), it seems appropriate to use the SMF to assist with the development of systems-oriented curriculum. The tasks can be designed to have students investigate each level (Relative Organization, Dimensions, Pathways) within the horizontal direction that is appropriate for the learners. For example, fourth graders would be expected to navigate object connections that are limited to interrelationships within a system. At this grade level, students are more likely to interrelate macro-objects. Meanwhile, the curriculum for high schoolers discussed here had students investigate multidimensional interrelationships connecting objects from different scales in networked pathways both within and between systems. The underlying principles that guided the development of the SMF help designers to identify the system under study, define boundaries and encourage development of abilities that have been postulated to advance understanding of how systems operate (Arnold & Wade, 2015; Assaraf & Orion, 2005).

As a framework that captures hierarchical principles shared by systems and mechanism, the SMF can be applied to systems other than environmental systems. Applicability of the SMF to a wide range of systems makes it a good framework to introduce to science teachers during professional development to foster the inclusion of tasks that promote abilities central to systems understanding. Researchers identify engaging teachers in active learning as one of the critical characteristics that describe effective professional development (Wilson, 2013). Because the SMF reflects principles of hierarchical arrangement of system structure, it is supported by the NGSS crosscutting concept of systems. The association of SMF with the unifying theme of systems has further implications in how teachers can collaborate during professional development to reflect on the NGSS theme of systems and how to develop this theme in their teaching practices. While investigating how the SMF represents the crosscutting concept of systems, teachers could restructure lesson sequence to align with the SMF to achieve a more coherent storyline. During professional development, SMF can also serve as a tool for teachers to actively engage in selecting or developing curriculum materials that will parallel learning progressions that promote students' systems understanding. Such an approach provides teachers with opportunities for repeated practice in the construction of curriculum with focused feedback and reduces the possibility of professional development that involves direct instruction in teaching practices.

Future research

This study presents limited but compelling empirical evidence that the Systems Matter Framework can serve as an assessment tool to capture students' progress in conceptualizing hierarchical organization of system structure. Although developed as a framework for the evaluation of concept maps, SMF could prove to be beneficial in evaluating other open-ended forms of assessment such as reflective writing and written essays. Research is needed to probe into the applicability of SMF to other contexts and uncover potential modifications that may strengthen this tool.

SMF is a framework that is substantiated by principles consistent with system structure. However, it was developed within a specific context, environmental systems. To test SMF for transferability to a different science content, this analytical framework needs to be examined in new contexts. It is possible that application of SMF in different contexts will provide opportunities for more linear, branched and network connections within and between systems that will further our understanding of the relationships between conceptualization of system structure and systems understanding. Further research may establish whether this framework is useful in evaluating systems across science disciplines.

Limitations

The validity of this framework needs to be further investigated. To examine generalizability, SMF needs to be tested in different settings. Further research studies with larger sample sizes and multiple points of assessment are needed to verify the claims about SMF. Large scale examination of SMF as an evaluation tool using a sample size of sufficient power has potential for examining the matching conceptualization of systems as students learn to interrelate objects within the hierarchical arrangement of the system structure.

Also, although this study examined how students conceptualize object connections within a system, it did not explicitly address students' conceptions of the molecular nature of matter objects, which limits the interpretation of the evaluation provided by the study. Students' in the same grade may have varying conceptions of molecular scale (Mohan et al., 2009). Therefore, even though the nitrogen containing objects were treated as molecular throughout the unit implementation, students may have perceived these objects at macro-scale. For instance, the evaluation of water and nitrate connection as macro to molecular object connection may be incorrect if the student interpreted both objects at macro-scale. On a related note, students' conceptions of molecular nature of matter objects may vary for different substances. Liu & Lesniak (2006) note that students' conceptualization of molecular scale of matter depends on the kind of substances (e.g. water vs nitrates). Although students interacted with water as macroscopic solvent during unit implementation, they also experienced the symbolic representation of water. Similarly, while nitrate was experienced as symbols within chemical formulas, nitrate levels were daily measured as part of a macroscopic solute.

Despite the fact that both substances were examined at both macro-level and at the level of molecular symbols, the emphasis was different for each substance. Therefore, students' conceptualization of molecular nature may have differed for nitrate and water. Since students' conceptions of molecular nature for different substances was not part of the analysis, potential inconsistencies in how students conceptualize the molecular scale of different objects within a system may have introduced a bias in the evaluation of concept maps which presents an additional limitation to this study.

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Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition, 80*(1-2), 1-46.
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Appendix A

Images Introduced to Students During Lesson 3

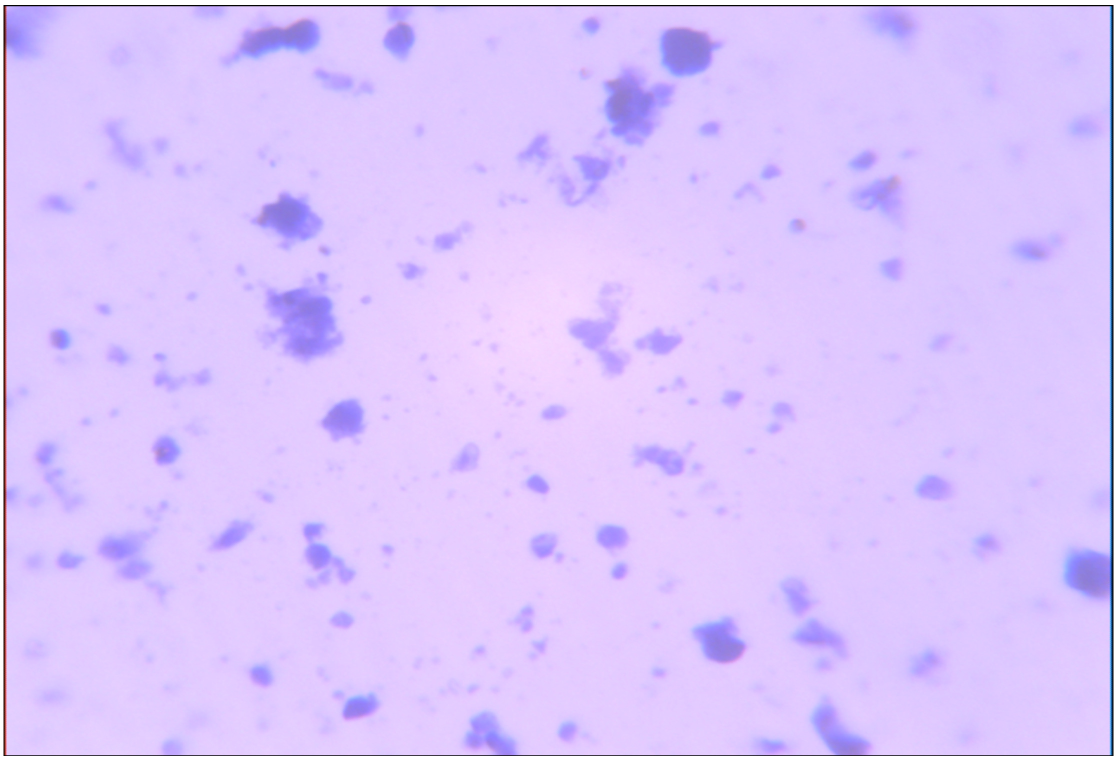


Figure 1. Light microscopic image of backyard soil

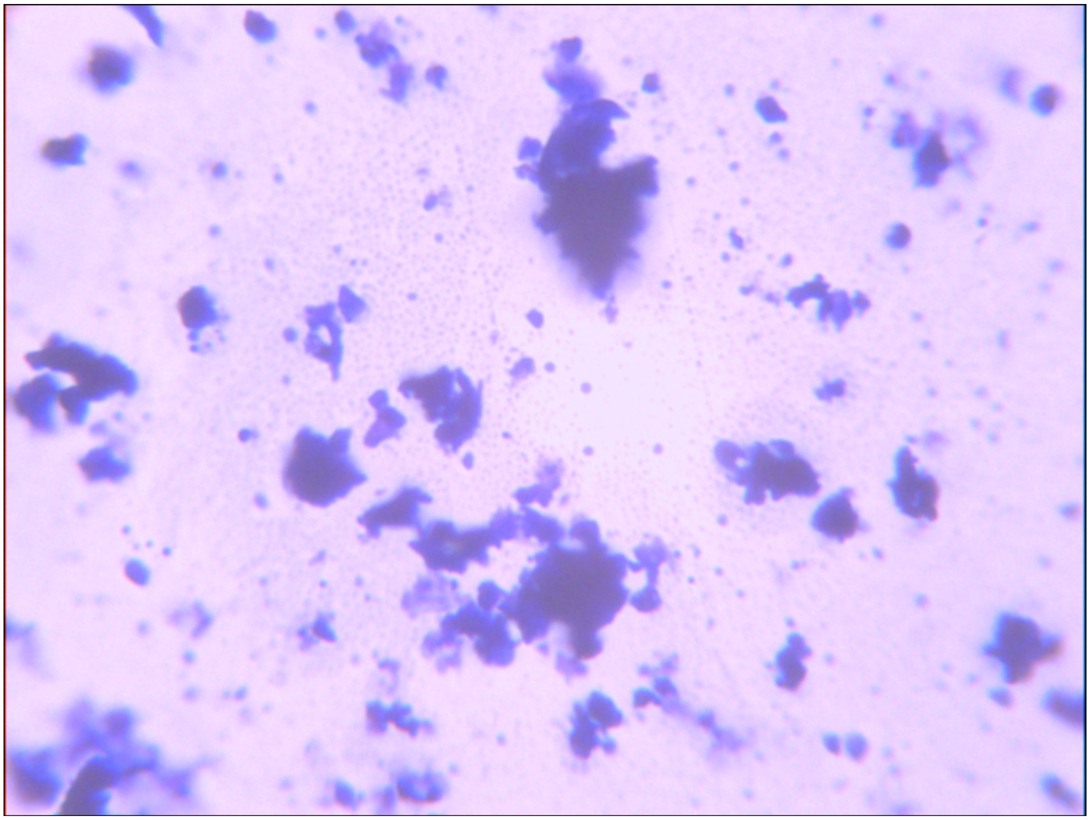


Figure 2. Light microscopic image of compost soil

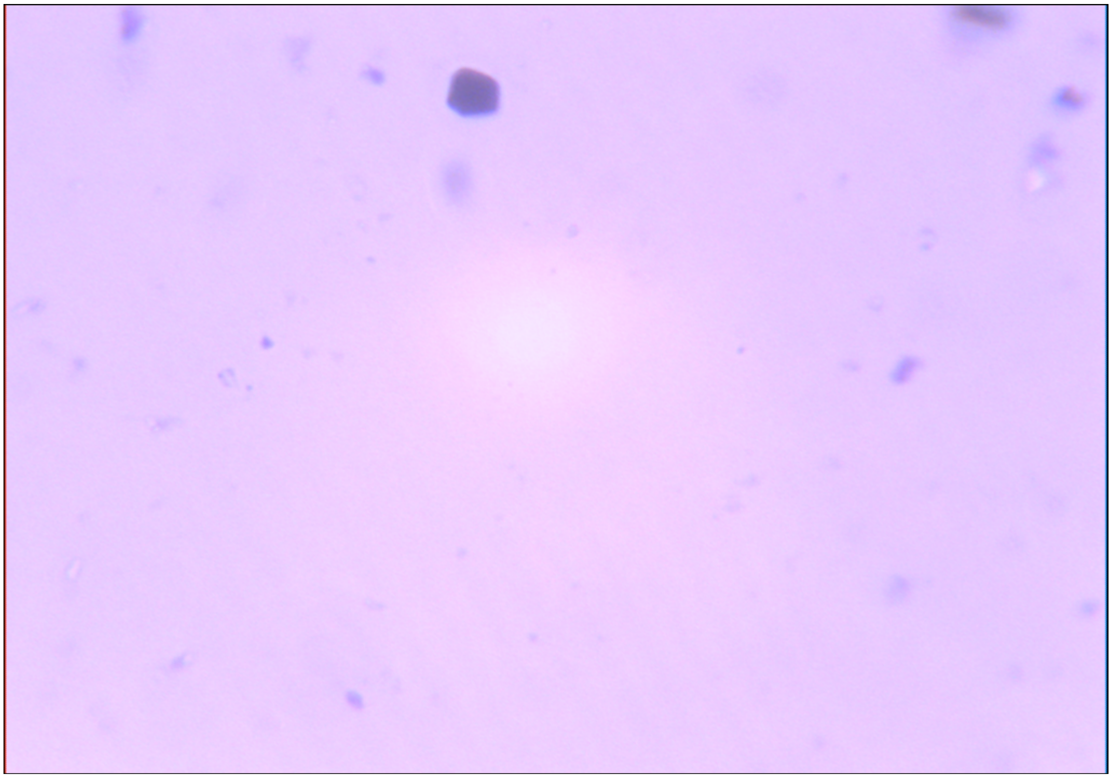


Figure 3. Light microscopic image of sandy soil

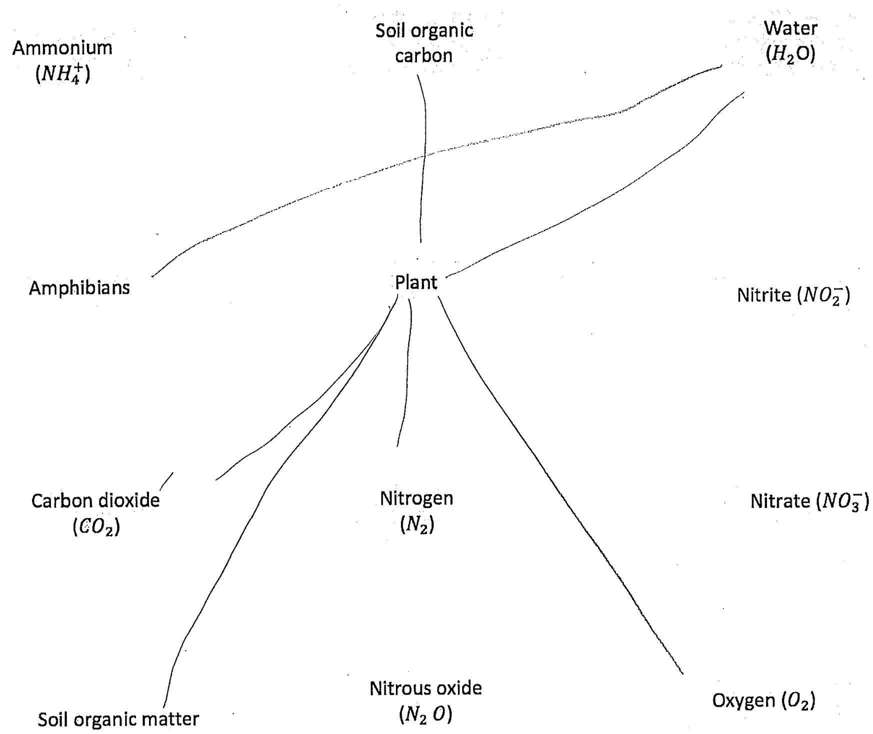
Appendix 1B

Original Pre-Concept Maps

111 (23)

In this concept map, you need to show your understanding of how these terms are connected.

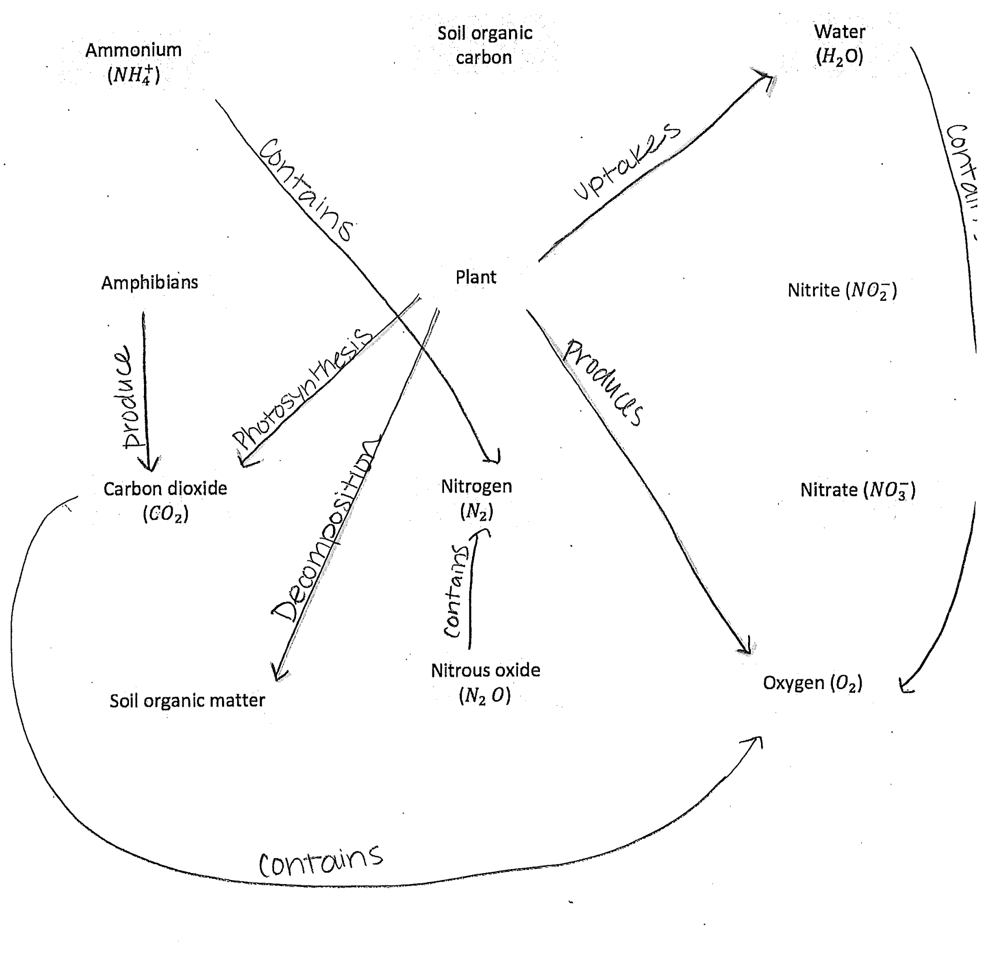
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



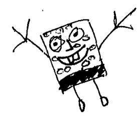
101 (6)

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links

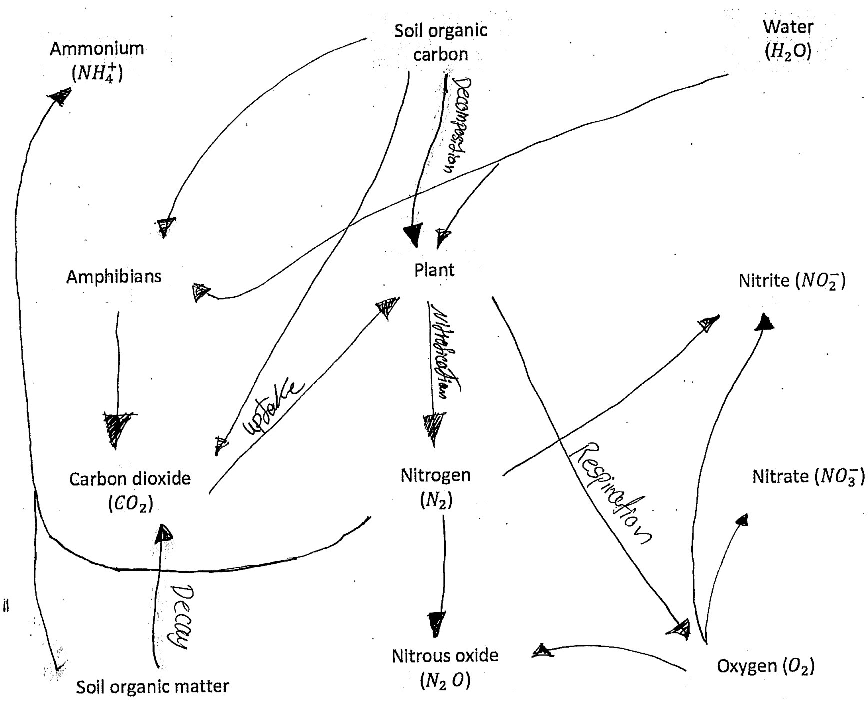


118 (46)



In this concept map, you need to show your understanding of how these terms are connected.

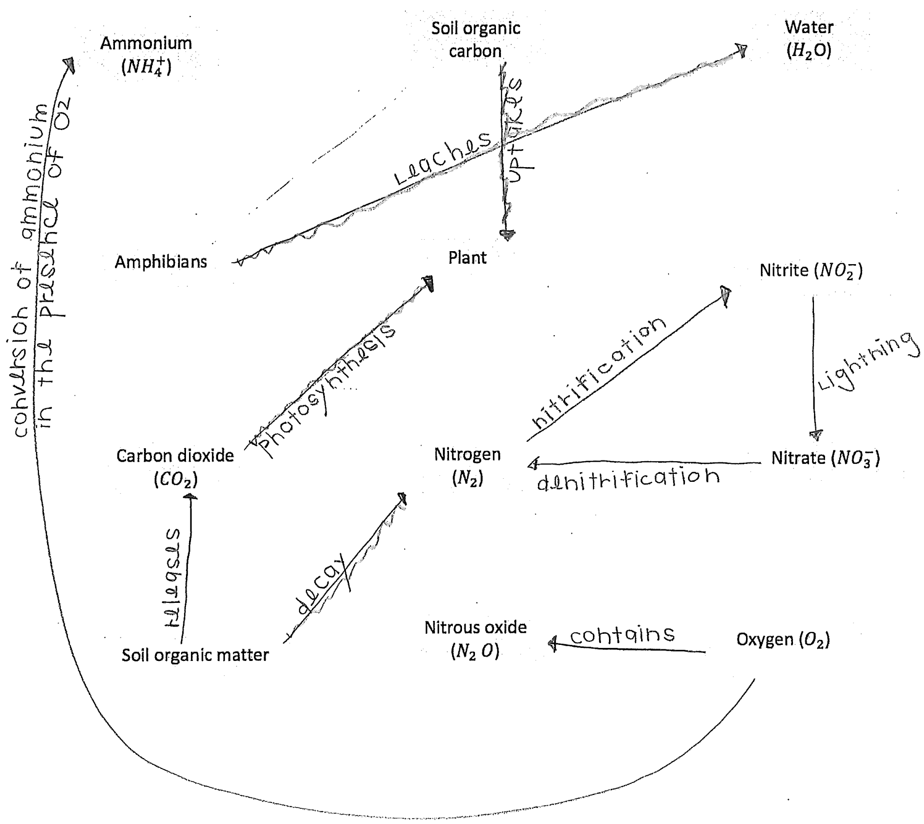
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



106(26)

In this concept map, you need to show your understanding of how these terms are connected.

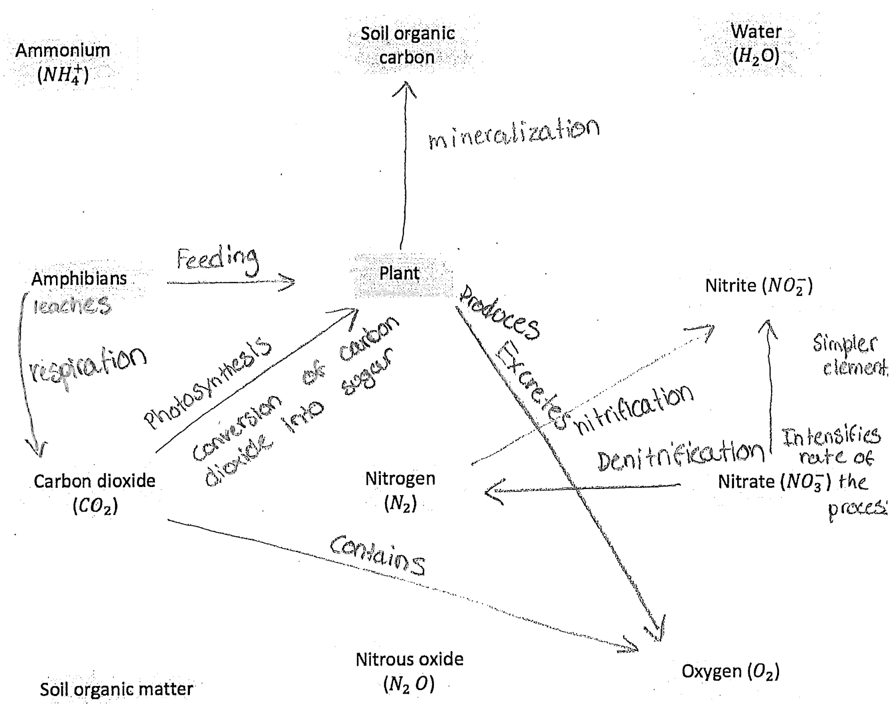
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



129 (19)

In this concept map, you need to show your understanding of how these terms are connected.

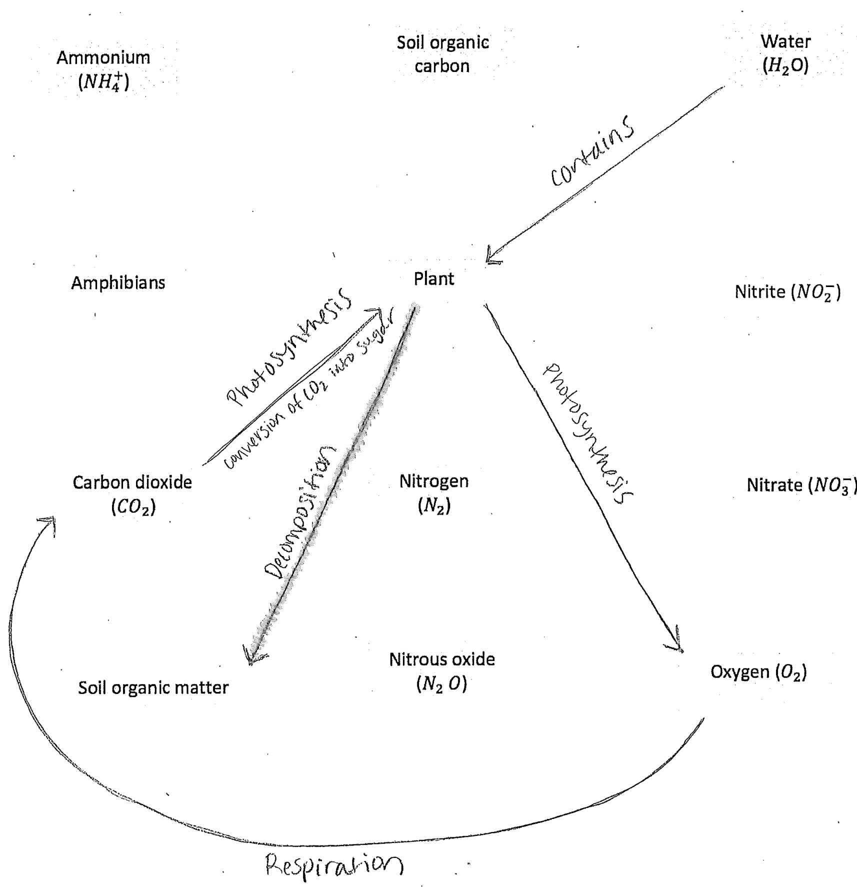
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



113 (14)

In this concept map, you need to show your understanding of how these terms are connected.

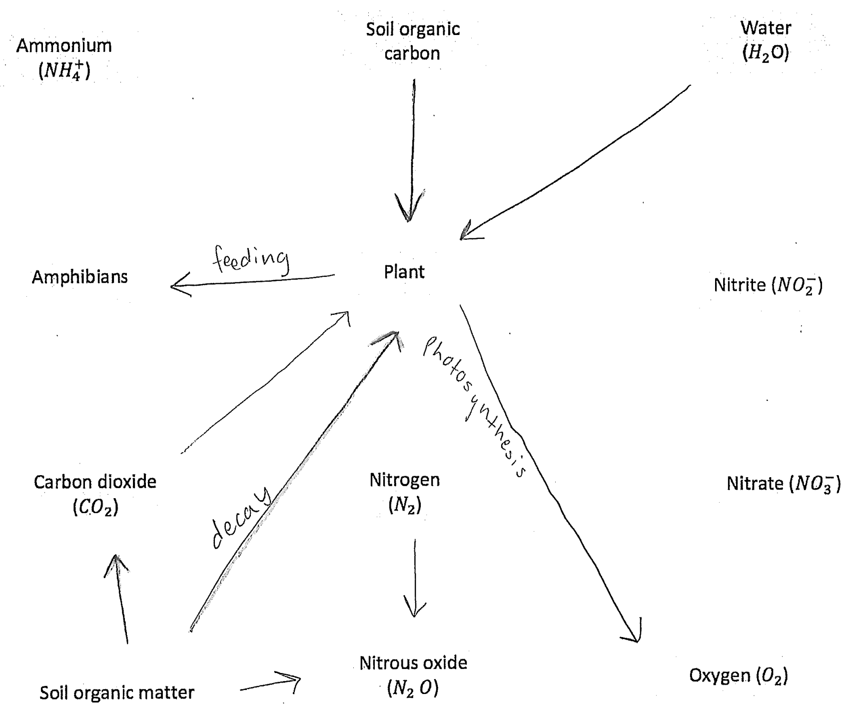
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



117 (48)

In this concept map, you need to show your understanding of how these terms are connected.

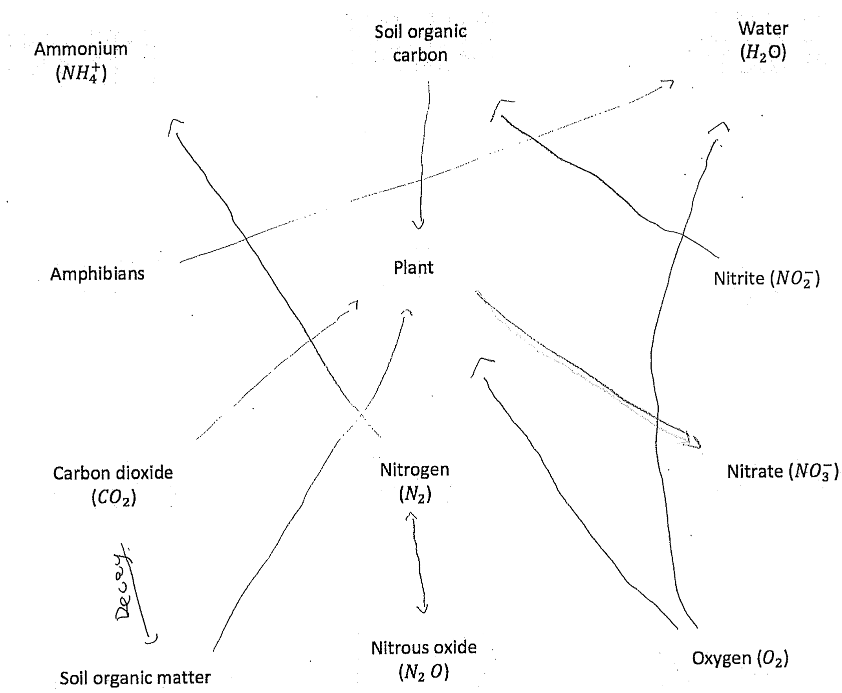
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



107 (9)

In this concept map, you need to show your understanding of how these terms are connected.

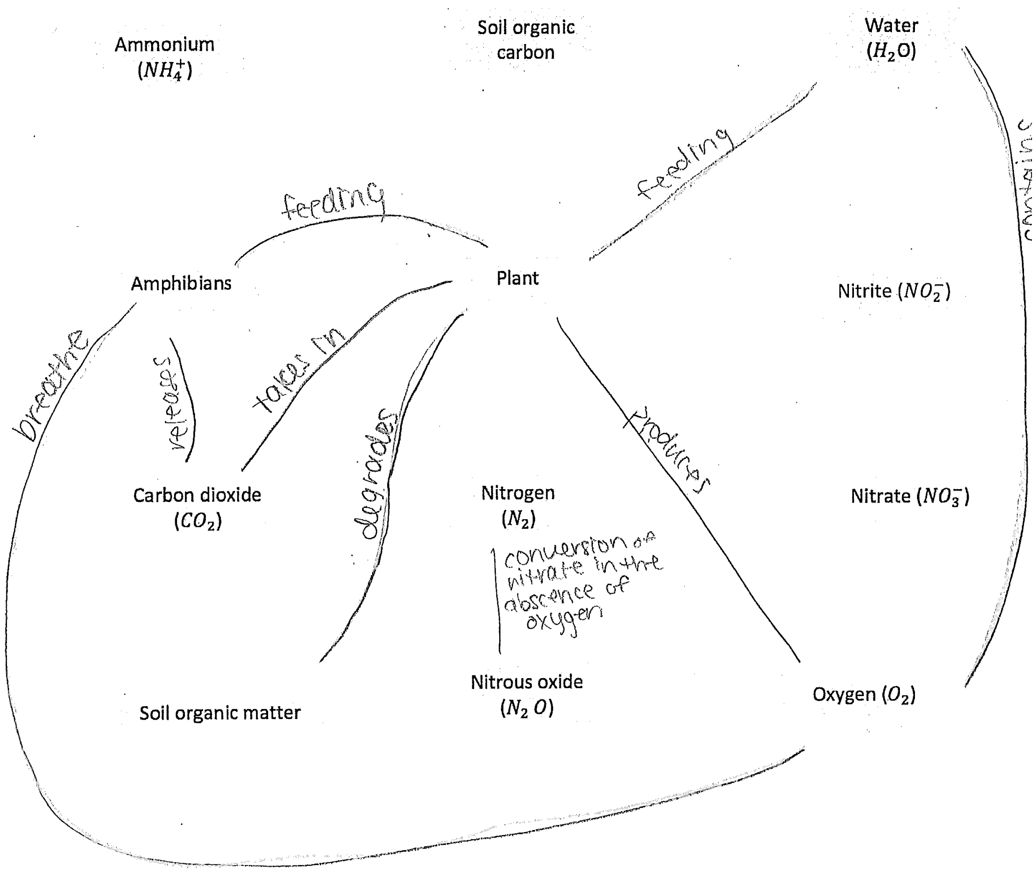
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



120(39)

In this concept map, you need to show your understanding of how these terms are connected.

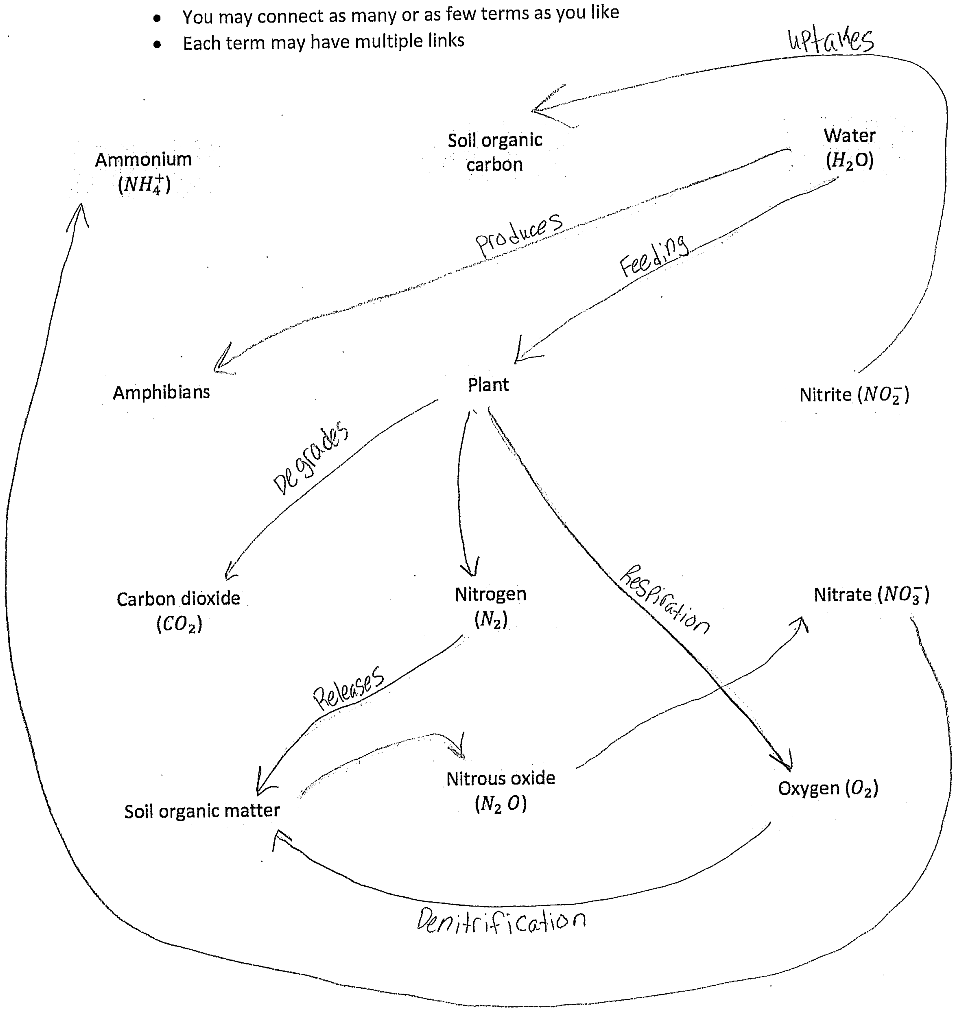
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



128(10)

In this concept map, you need to show your understanding of how these terms are connected.

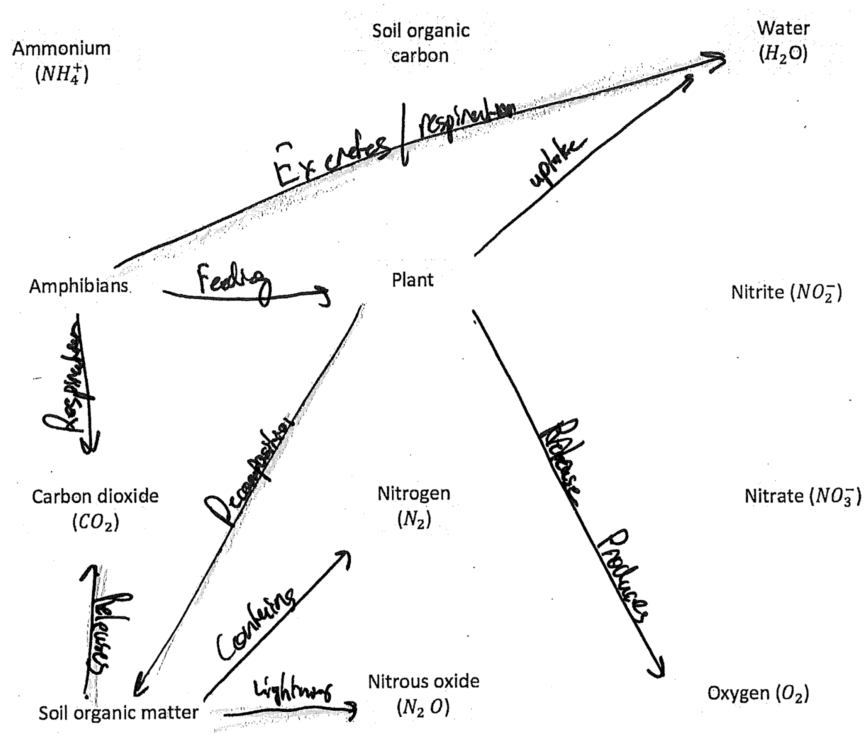
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



116 (8)

In this concept map, you need to show your understanding of how these terms are connected.

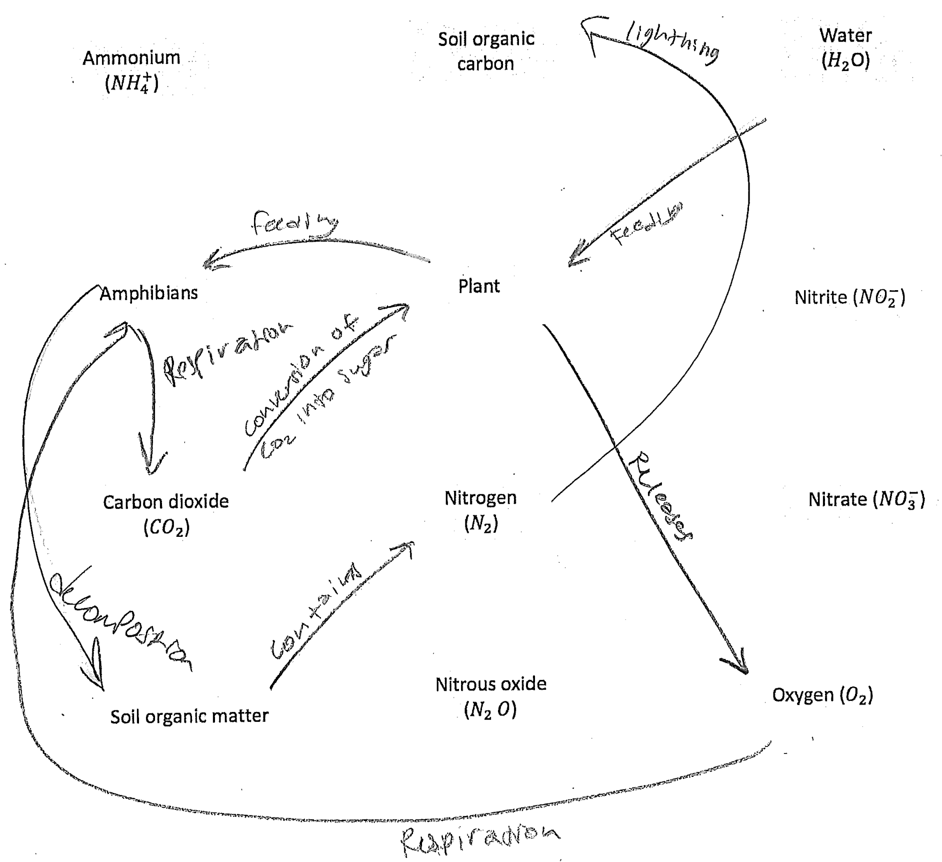
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



102(29)

In this concept map, you need to show your understanding of how these terms are connected.

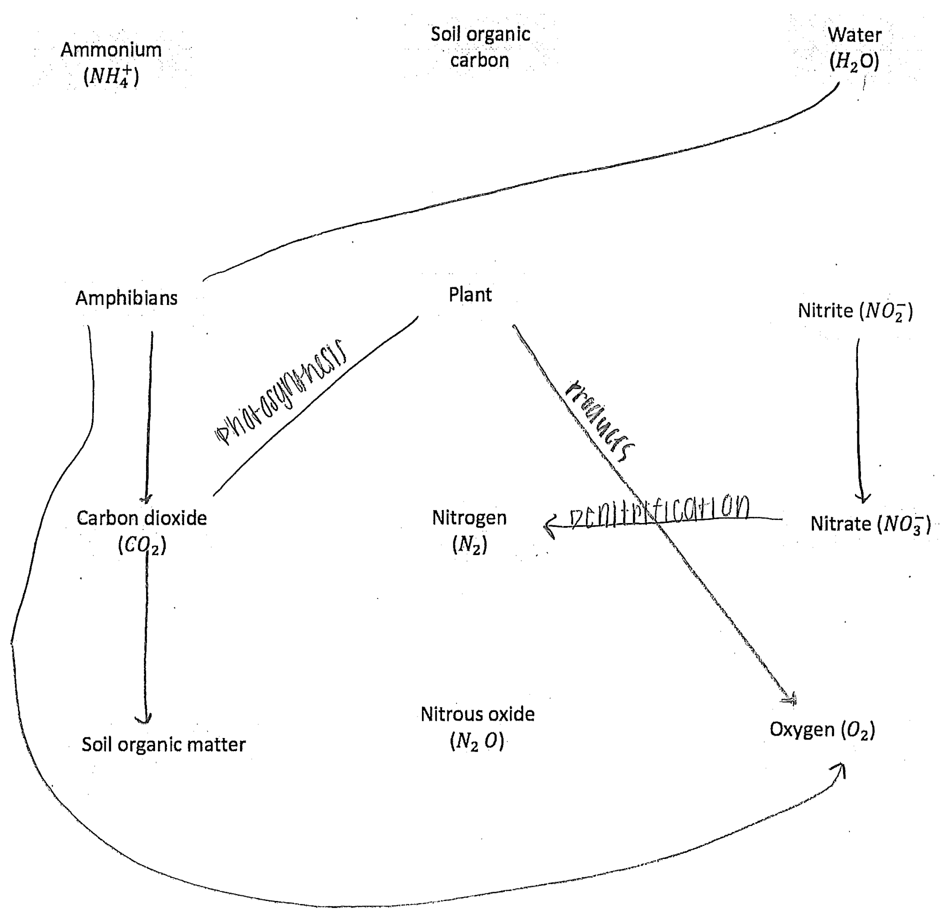
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



104(31).

In this concept map, you need to show your understanding of how these terms are connected.

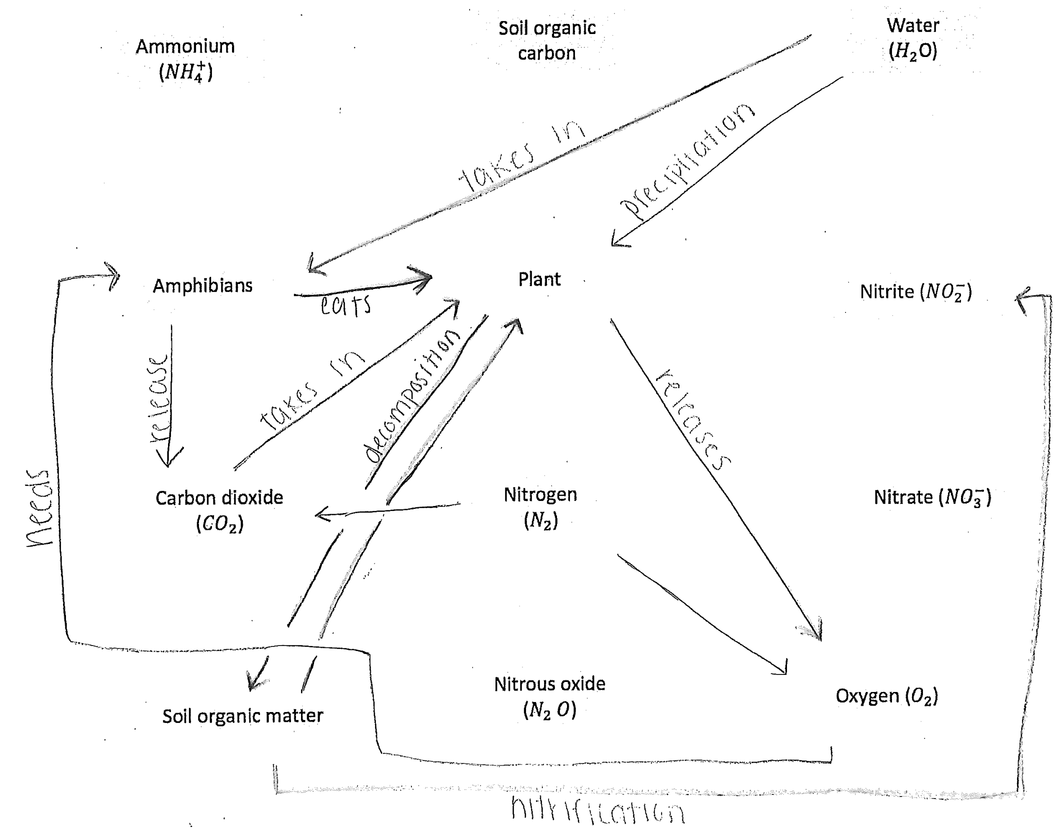
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



123 (20)

In this concept map, you need to show your understanding of how these terms are connected.

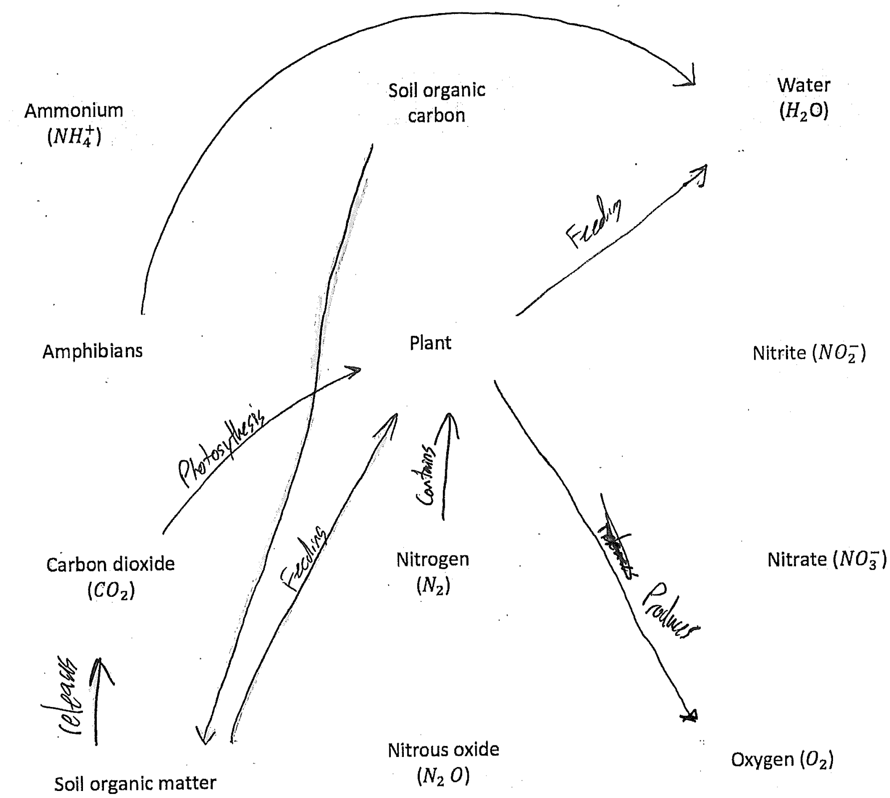
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



100 (30).

In this concept map, you need to show your understanding of how these terms are connected.

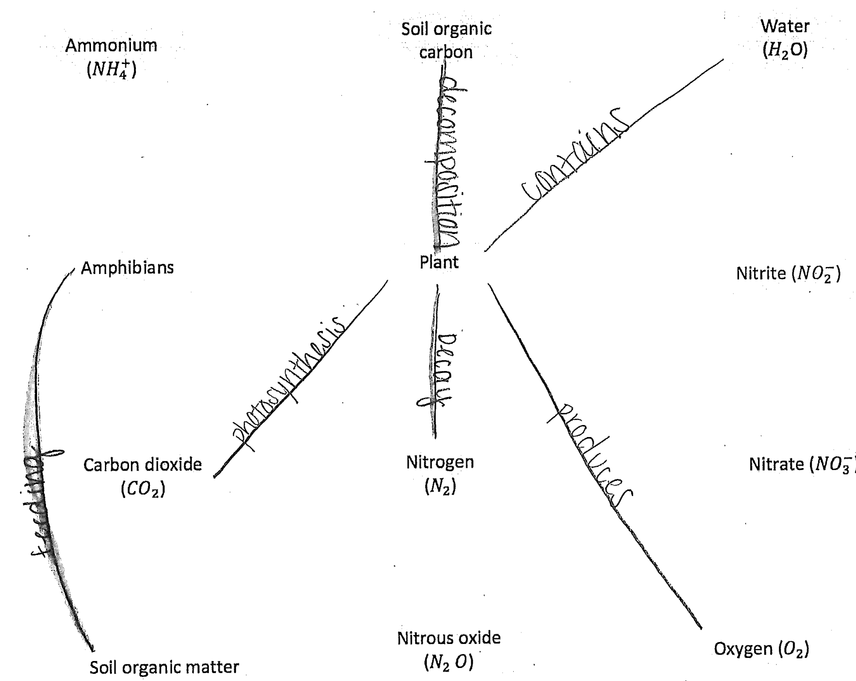
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



105(11)

In this concept map, you need to show your understanding of how these terms are connected.

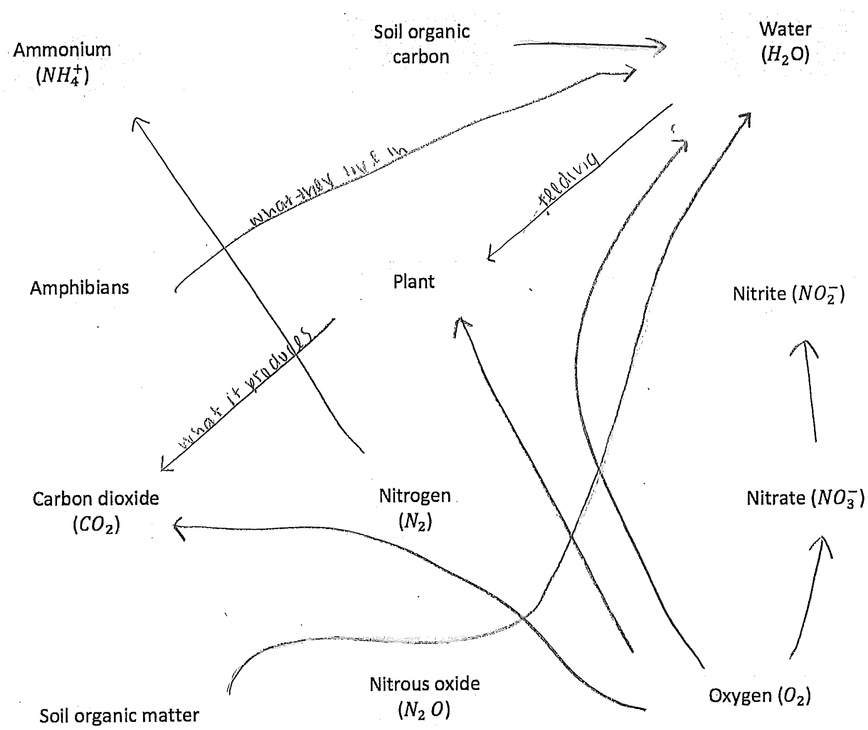
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



121 (151.

In this concept map, you need to show your understanding of how these terms are connected.

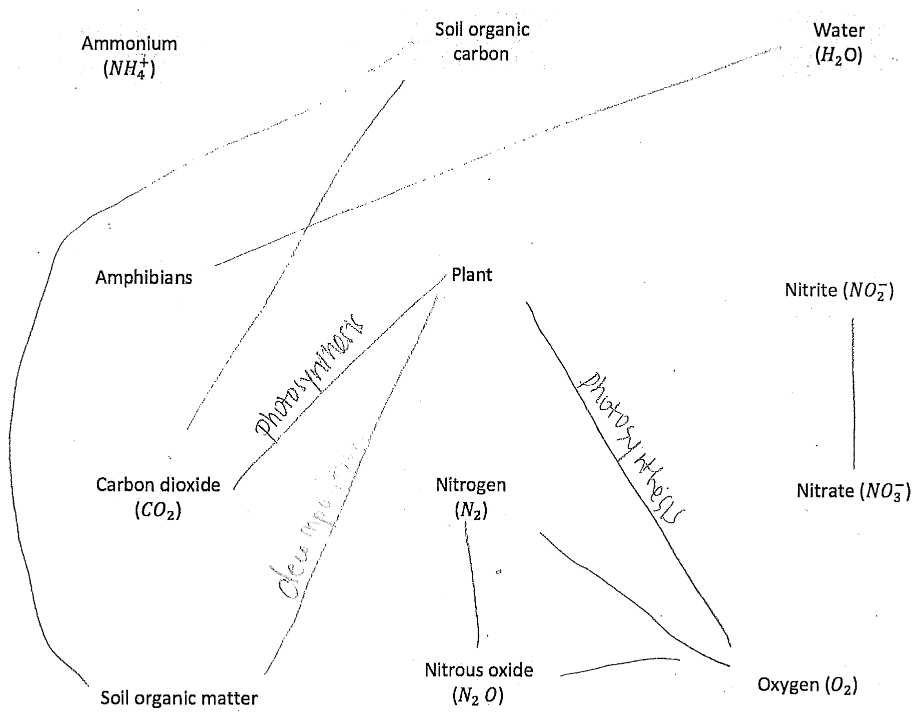
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



122 (16)

In this concept map, you need to show your understanding of how these terms are connected.

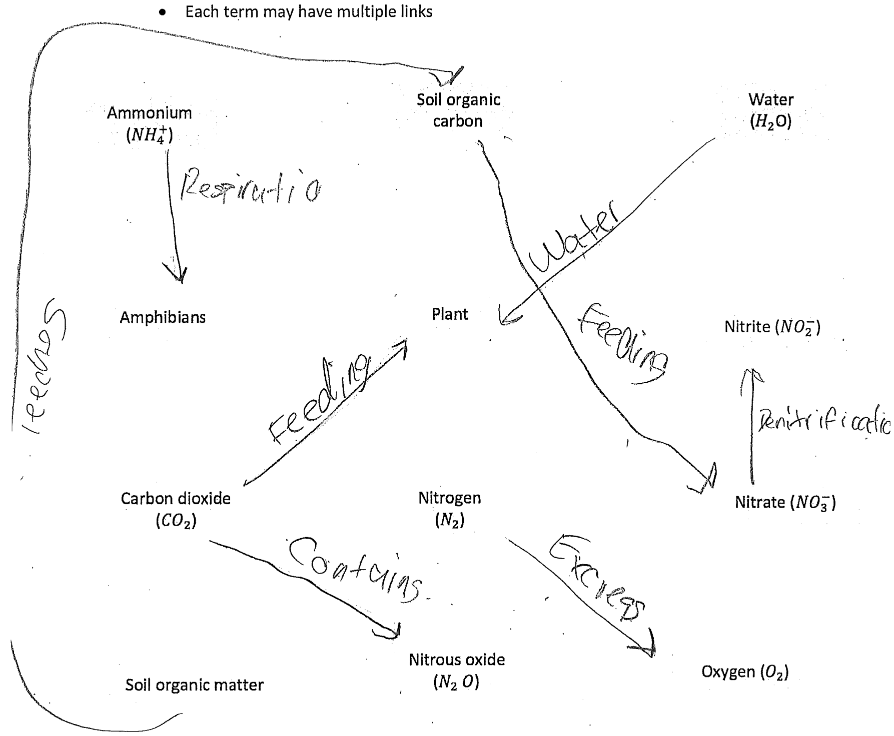
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



126(32)

In this concept map, you need to show your understanding of how these terms are connected.

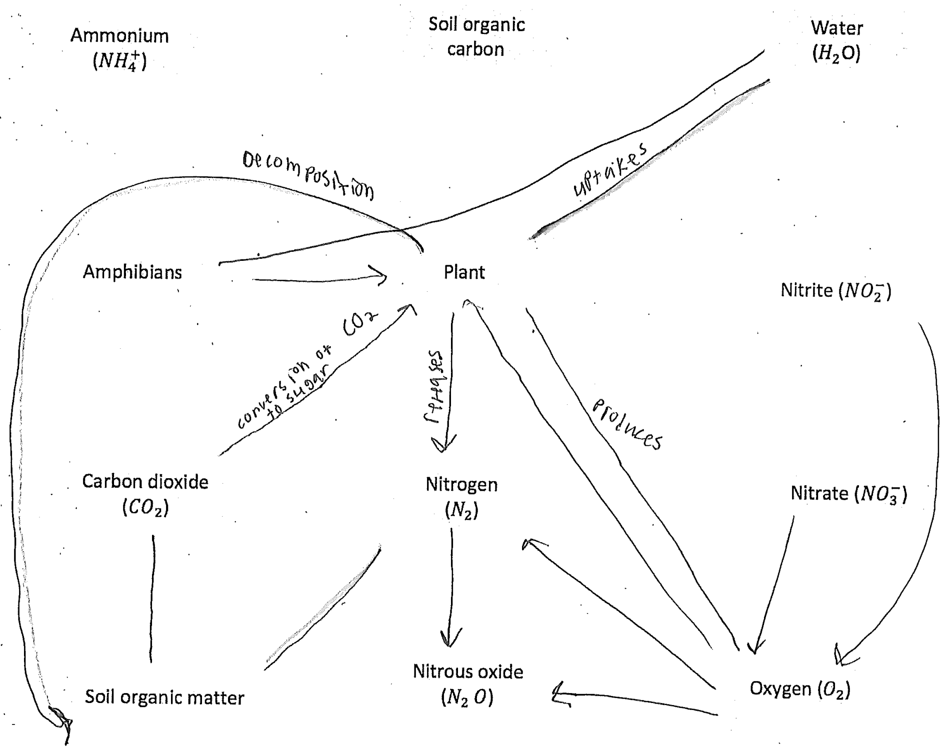
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



103(45)

In this concept map, you need to show your understanding of how these terms are connected.

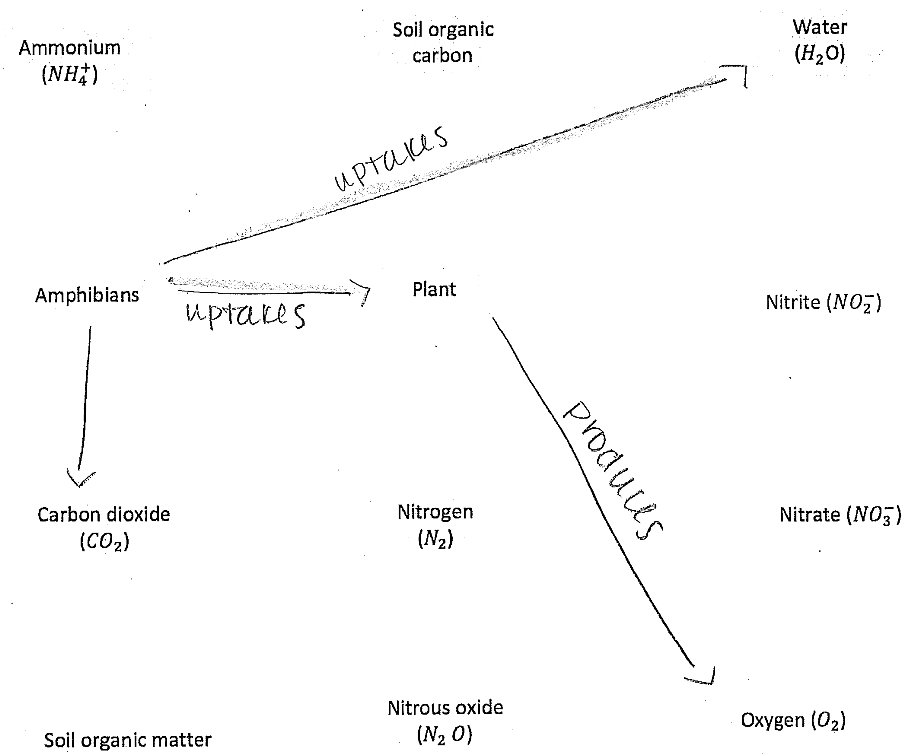
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



119(1)

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



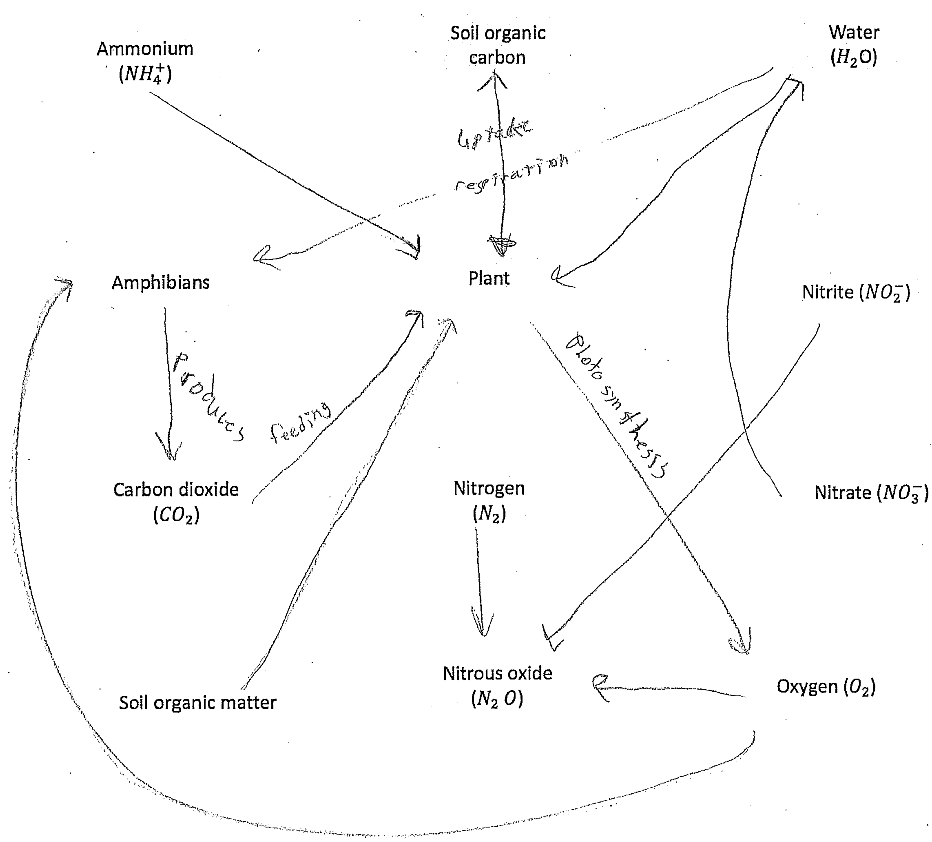
Appendix 2B

Original Post-Concept Maps

111 (50)

In this concept map, you need to show your understanding of how these terms are connected.

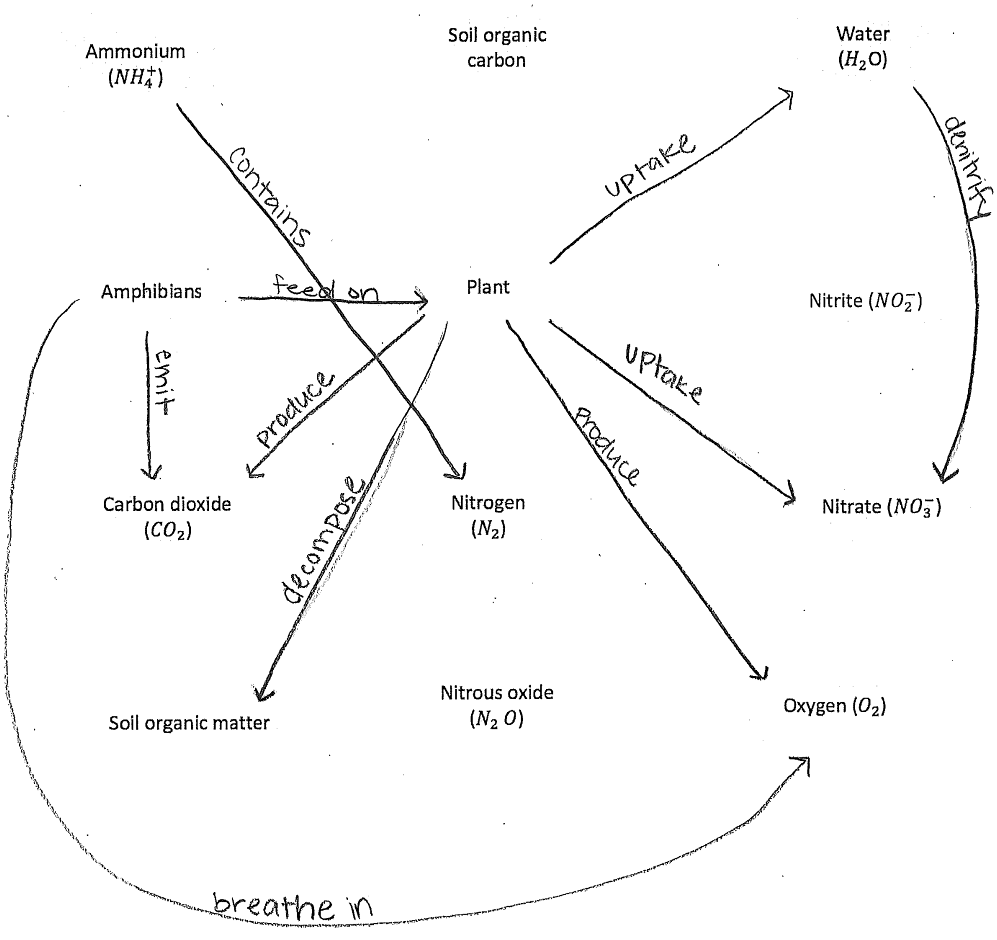
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



101 (53)

In this concept map, you need to show your understanding of how these terms are connected.

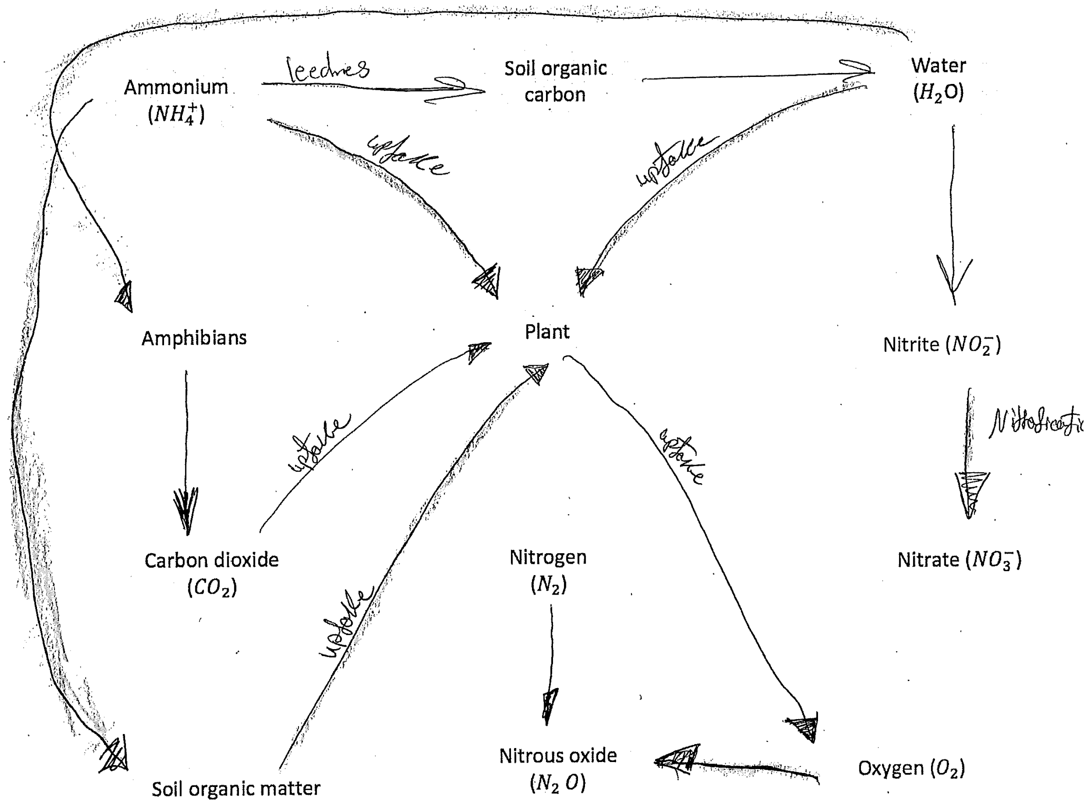
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



118 (33)

In this concept map, you need to show your understanding of how these terms are connected.

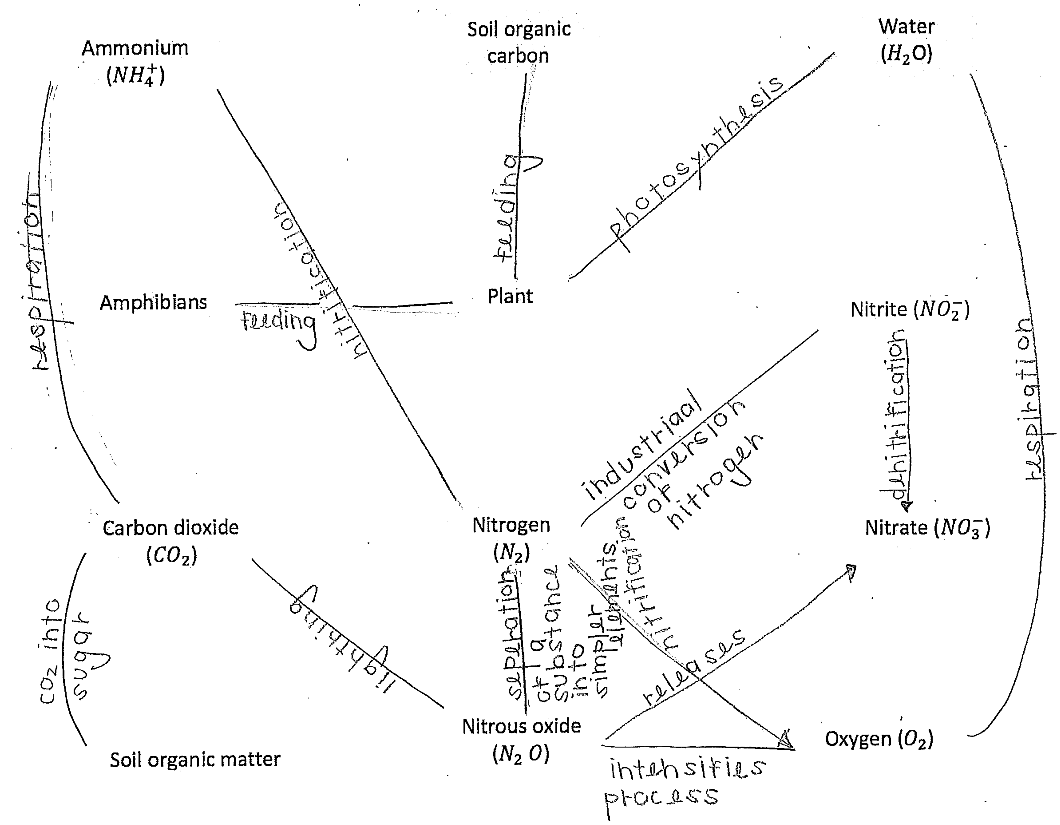
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



106 (52)

In this concept map, you need to show your understanding of how these terms are connected.

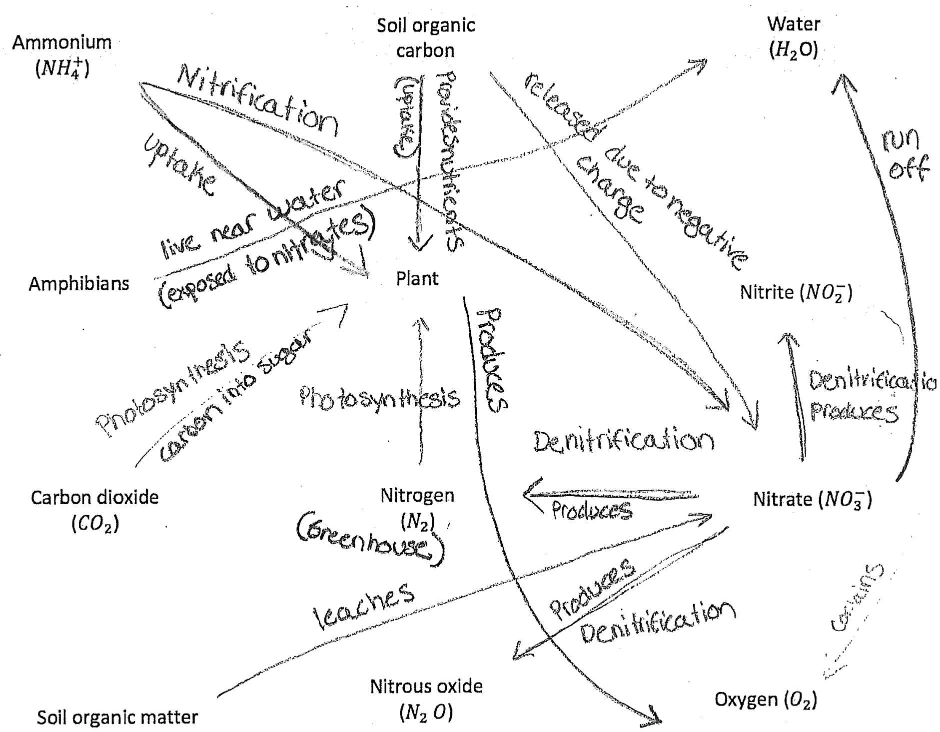
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



129 (44)

In this concept map, you need to show your understanding of how these terms are connected.

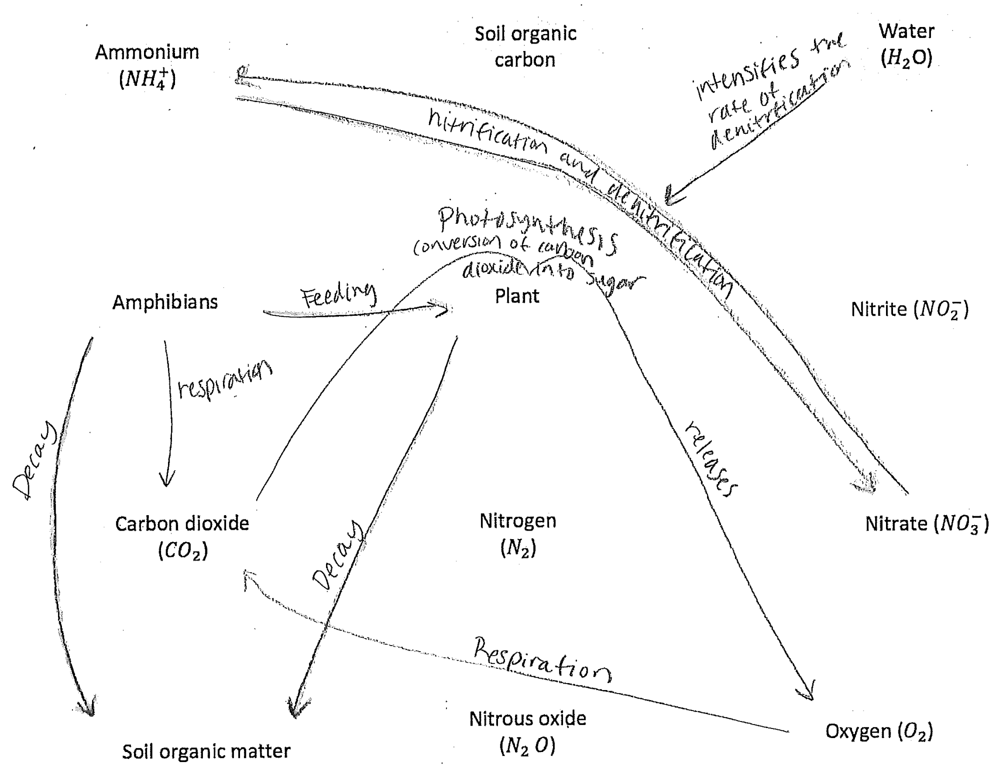
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



113(57)

In this concept map, you need to show your understanding of how these terms are connected.

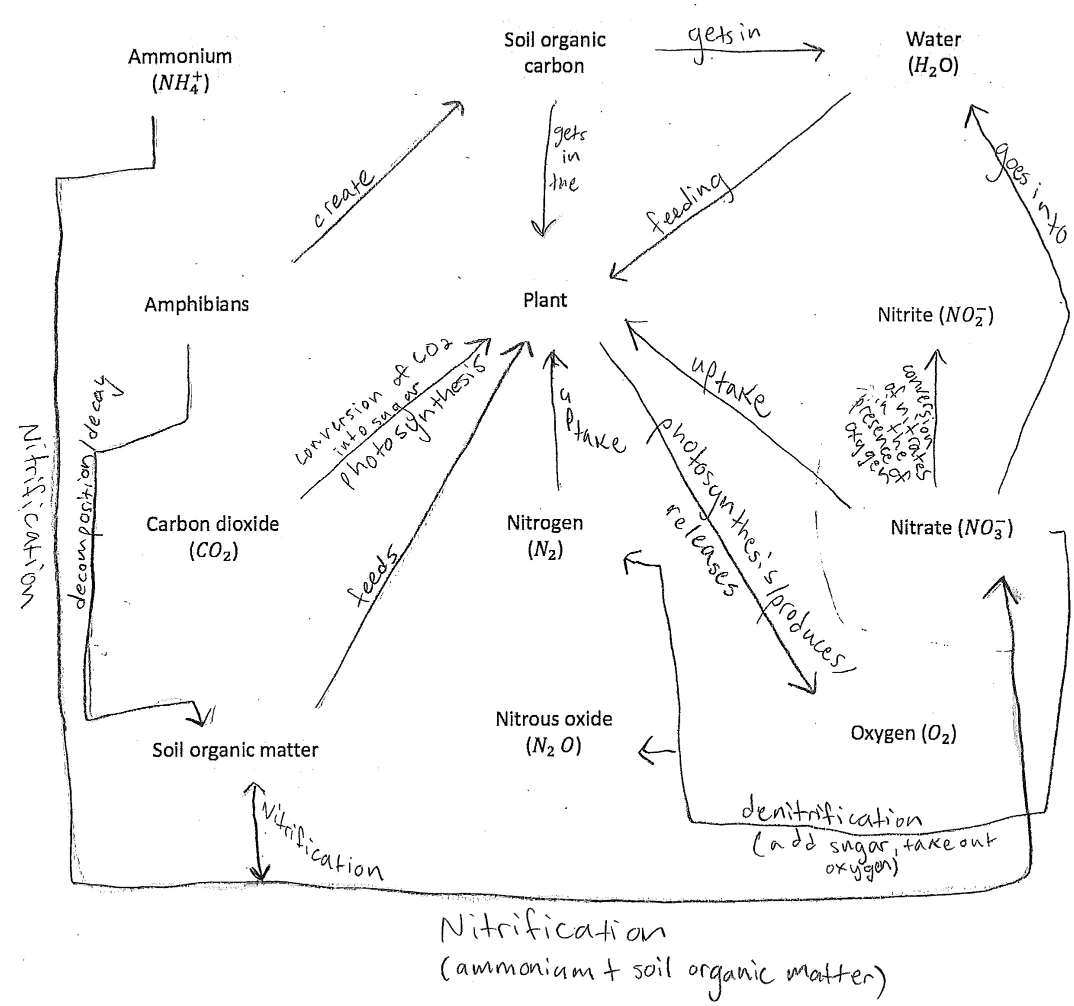
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



117 (5)

In this concept map, you need to show your understanding of how these terms are connected.

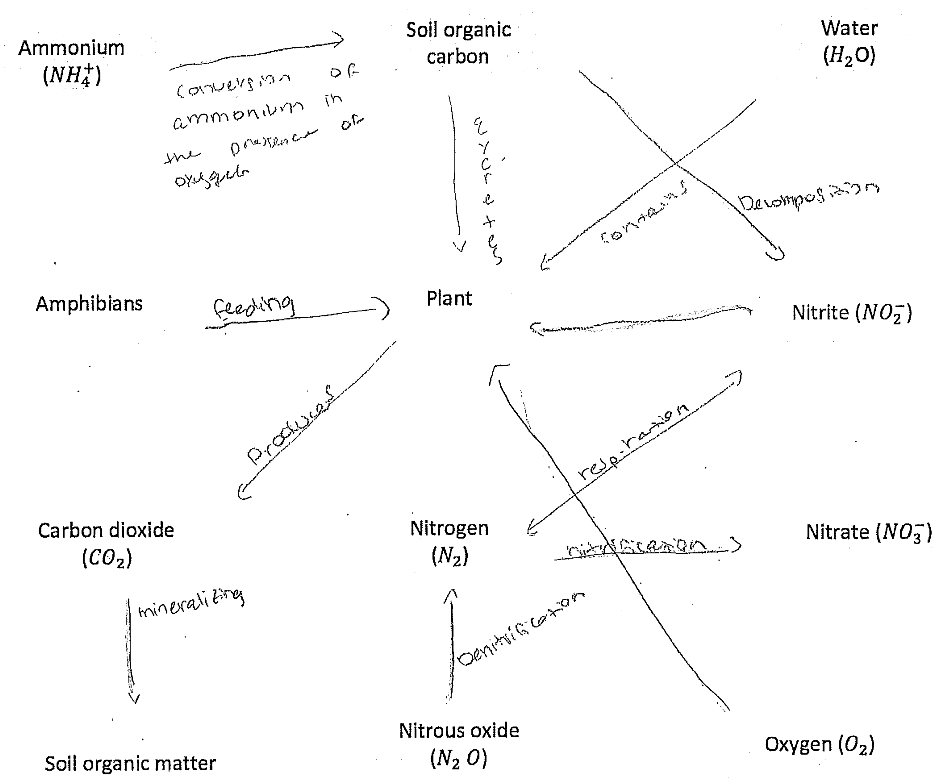
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



107(13)

In this concept map, you need to show your understanding of how these terms are connected.

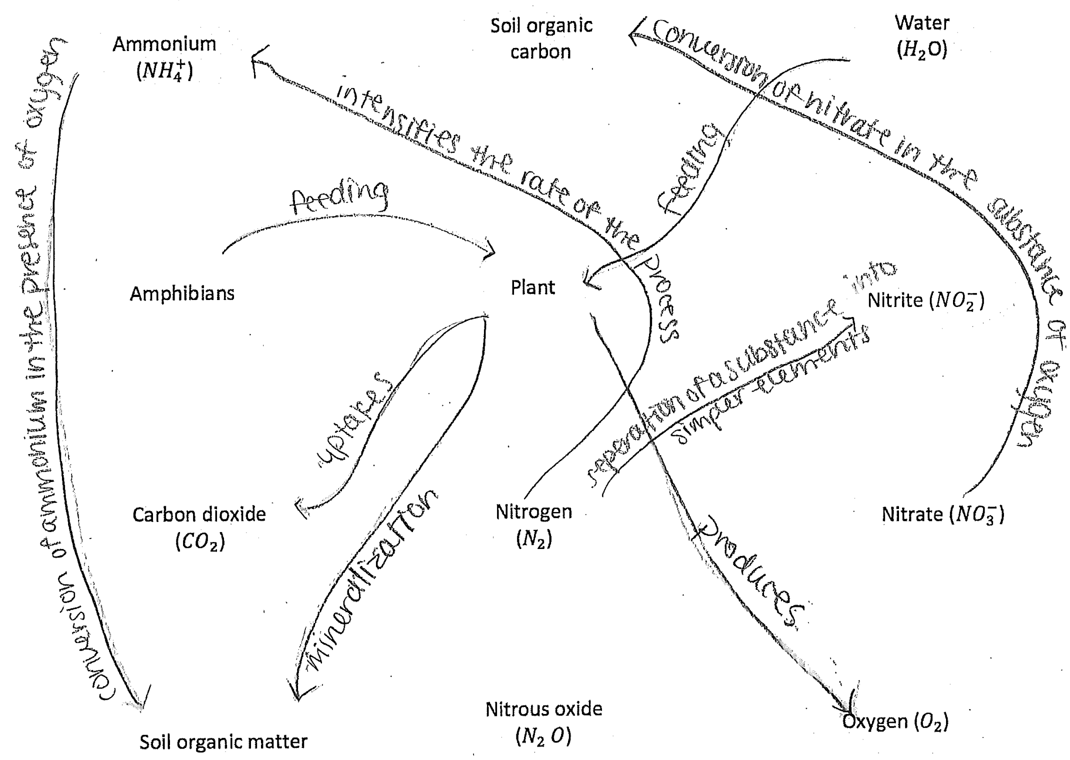
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



120(28)

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links

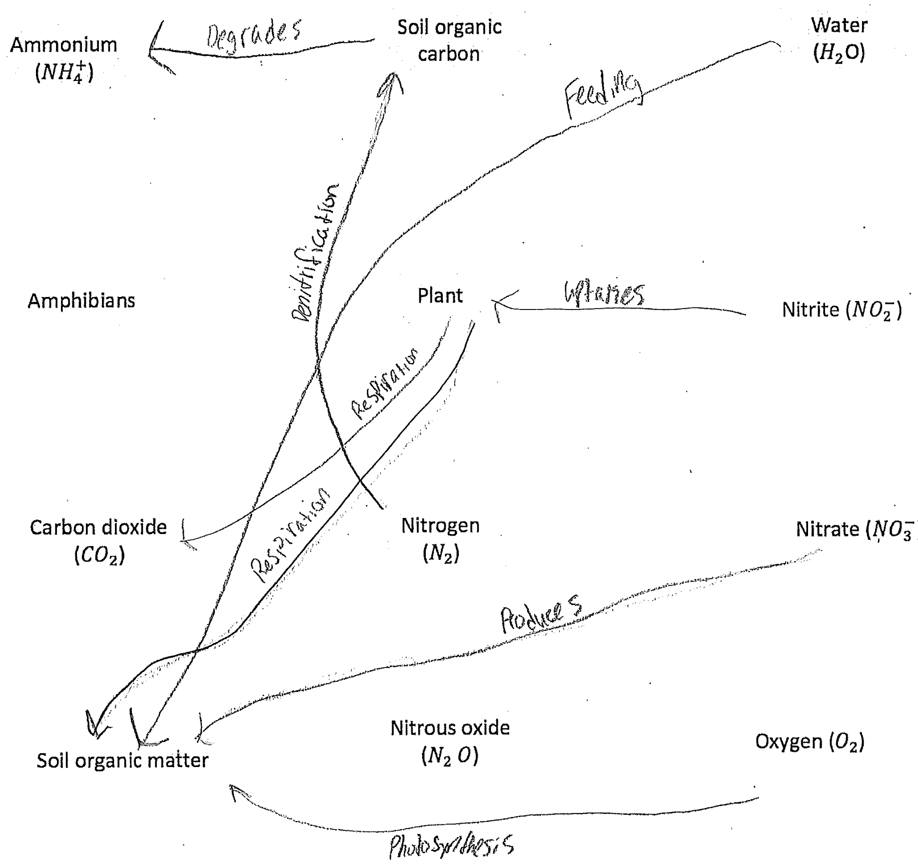


128(36)

Na

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links

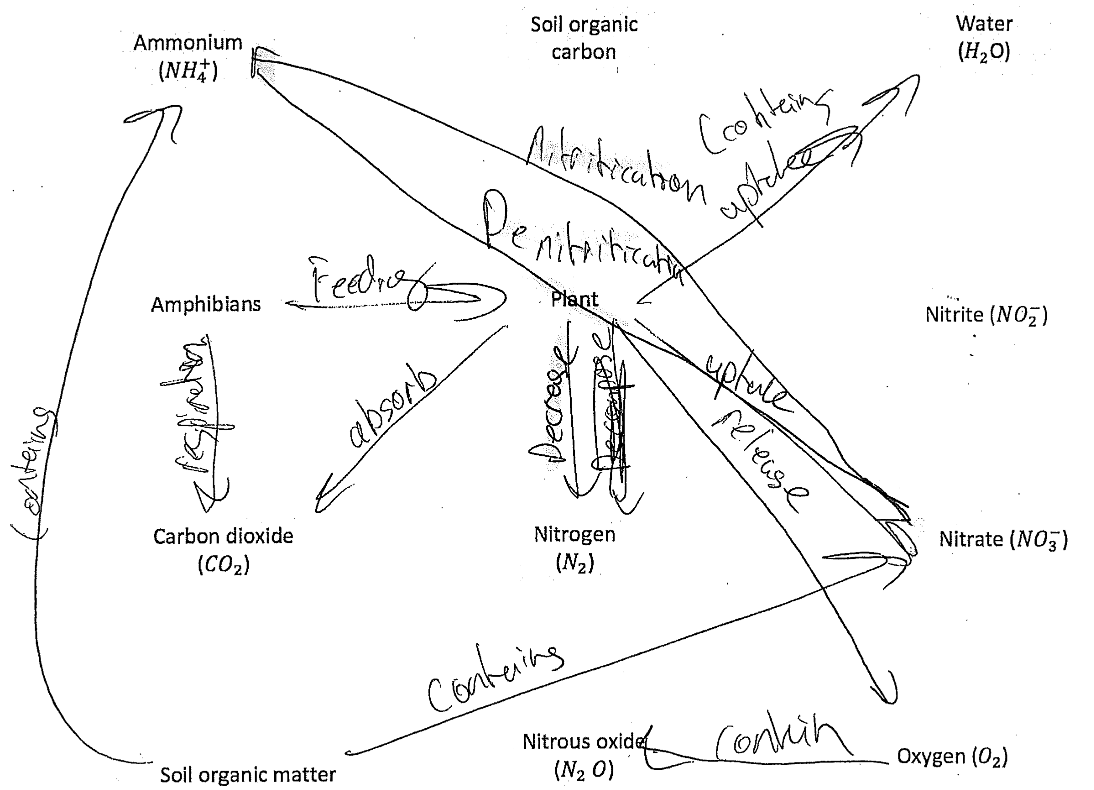


116 (49)

Reverse arrows All of them

In this concept map, you need to show your understanding of how these terms are connected.

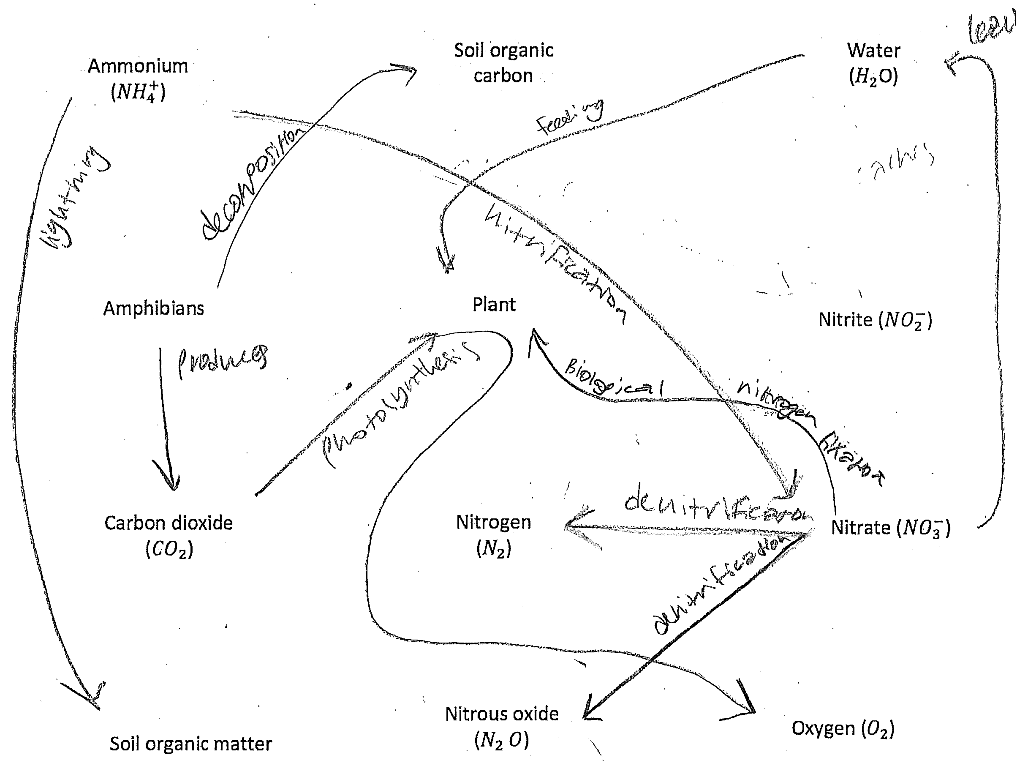
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



102 (22)

In this concept map, you need to show your understanding of how these terms are connected.

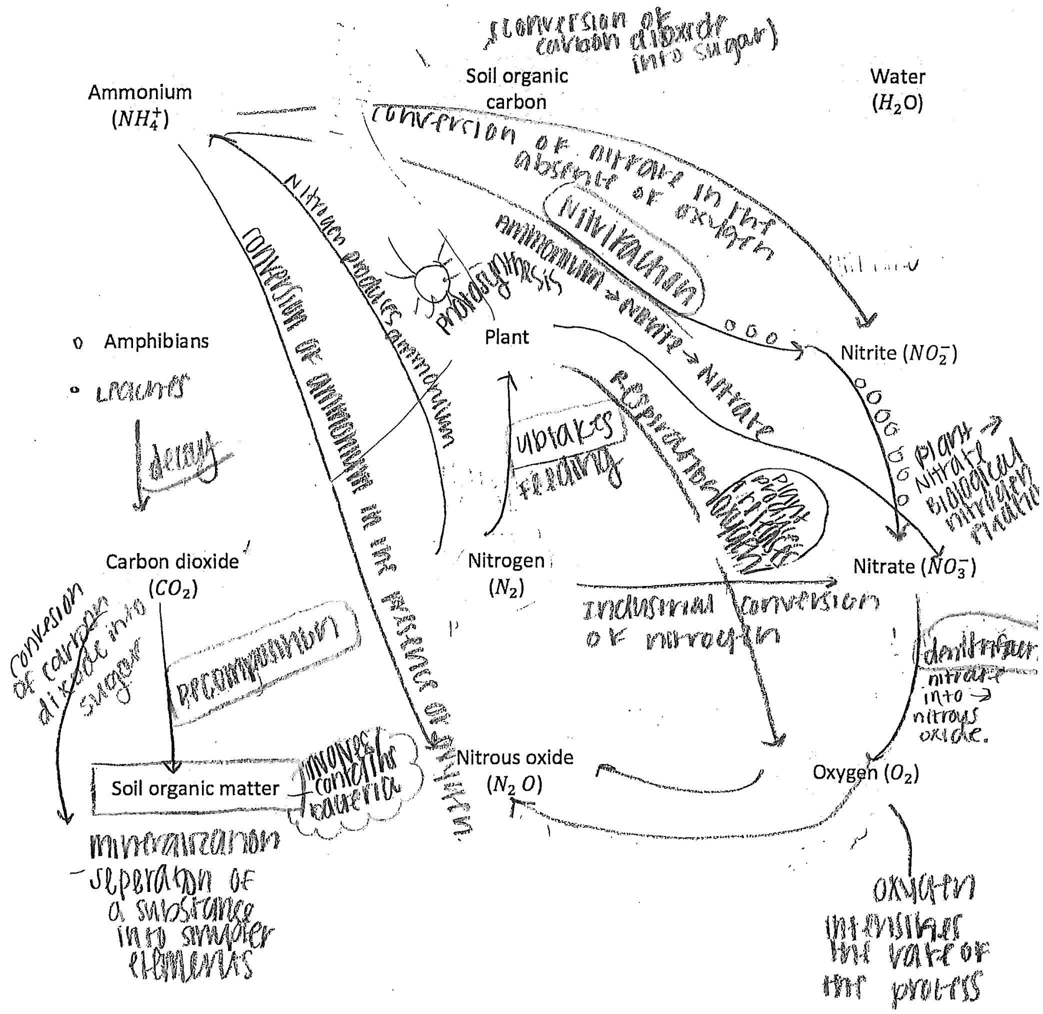
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



104(2).

In this concept map, you need to show your understanding of how these terms are connected.

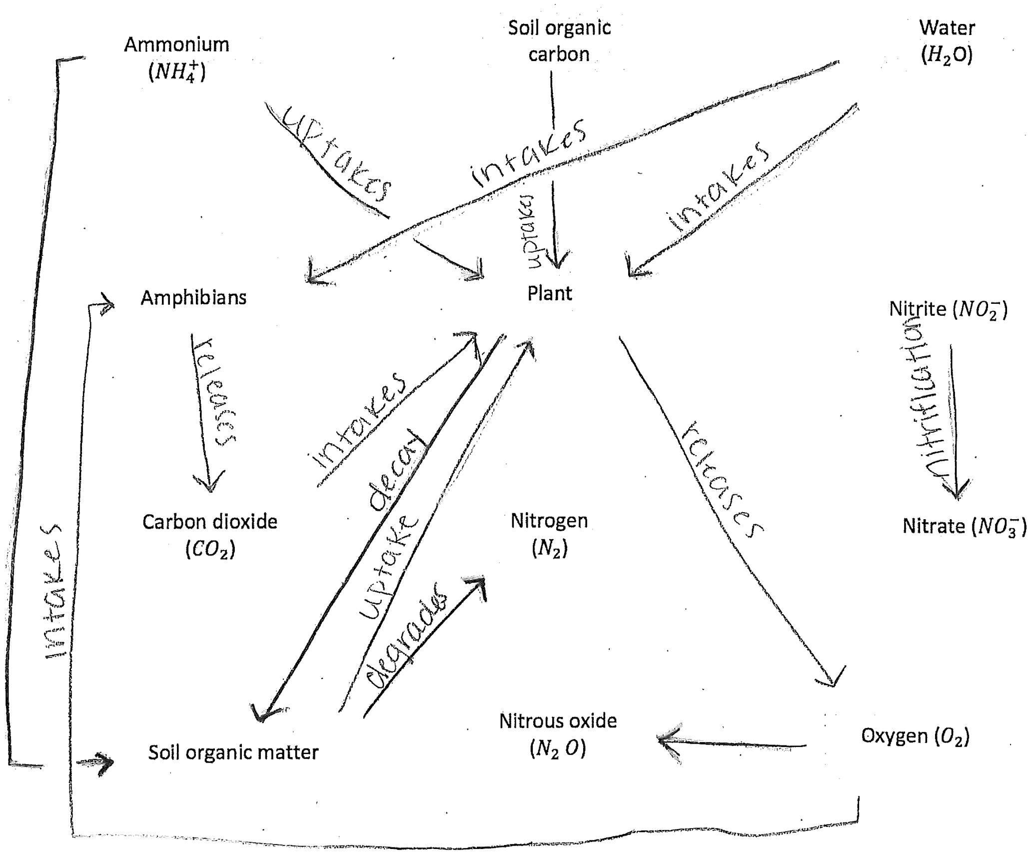
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



123(38)

In this concept map, you need to show your understanding of how these terms are connected.

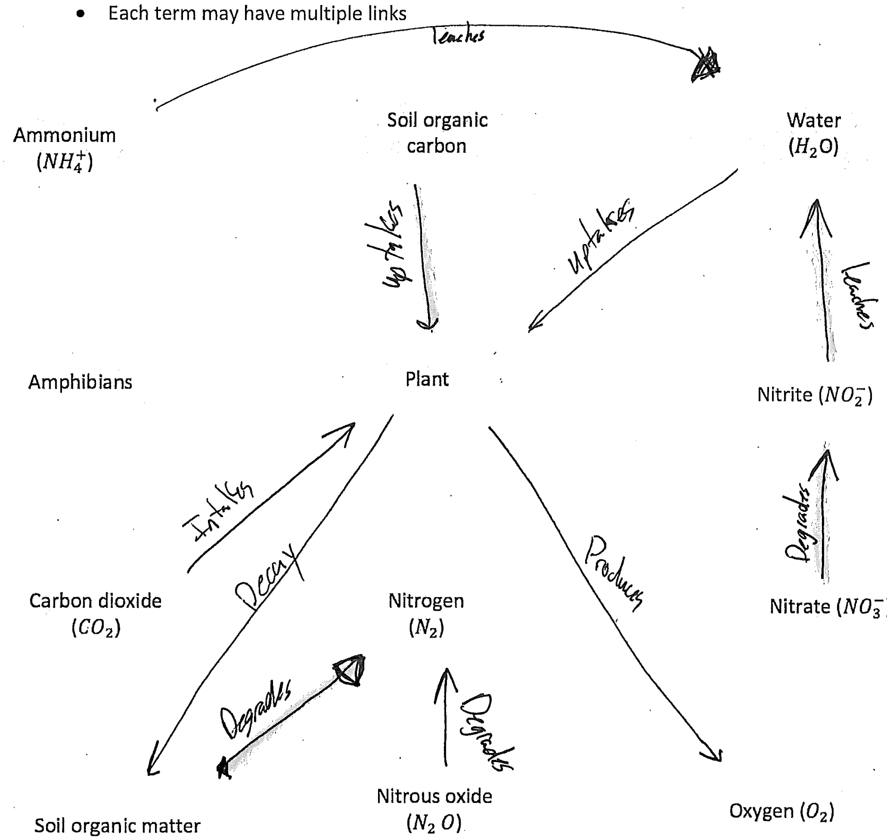
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



100(71.

In this concept map, you need to show your understanding of how these terms are connected.

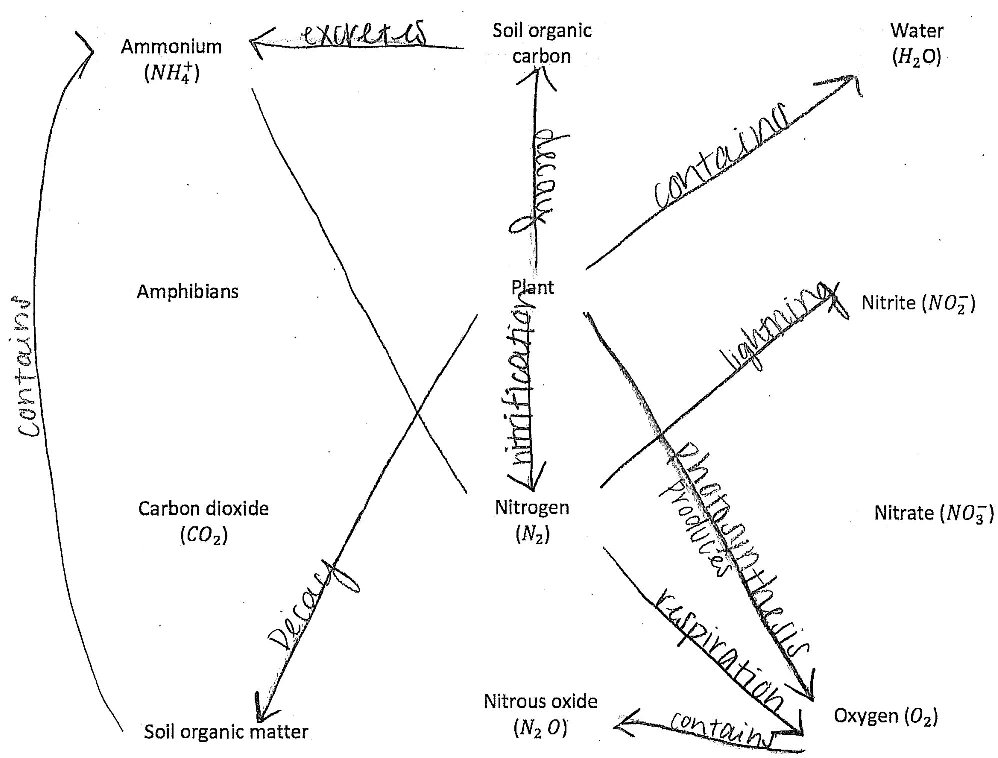
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



105(35).

In this concept map, you need to show your understanding of how these terms are connected.

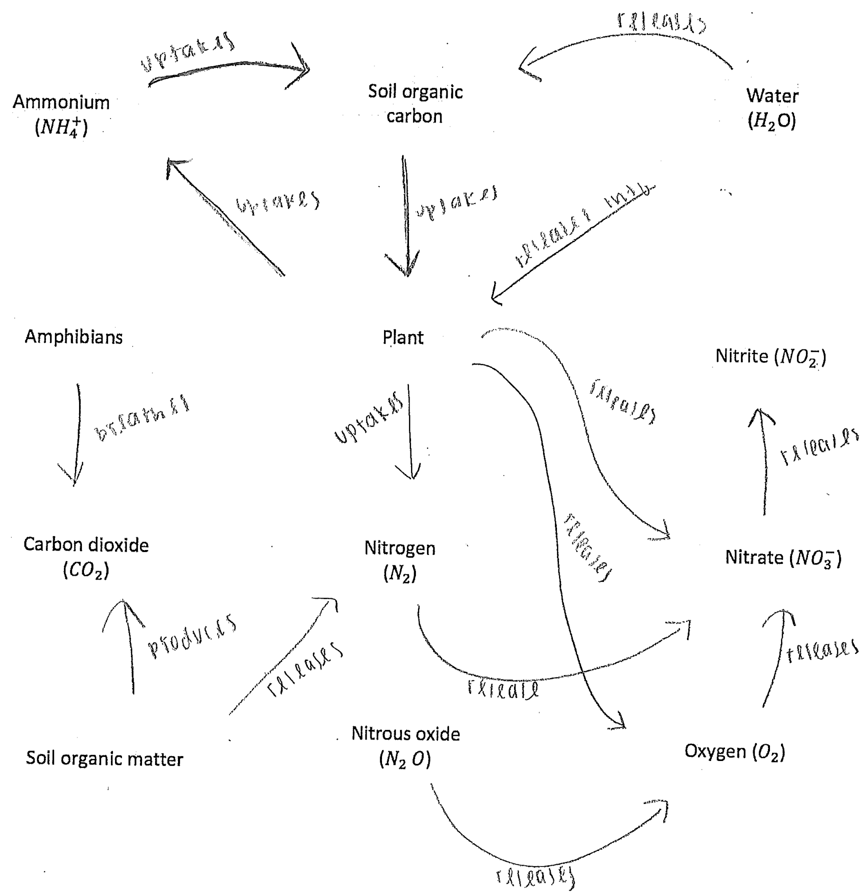
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



121 (37)

In this concept map, you need to show your understanding of how these terms are connected.

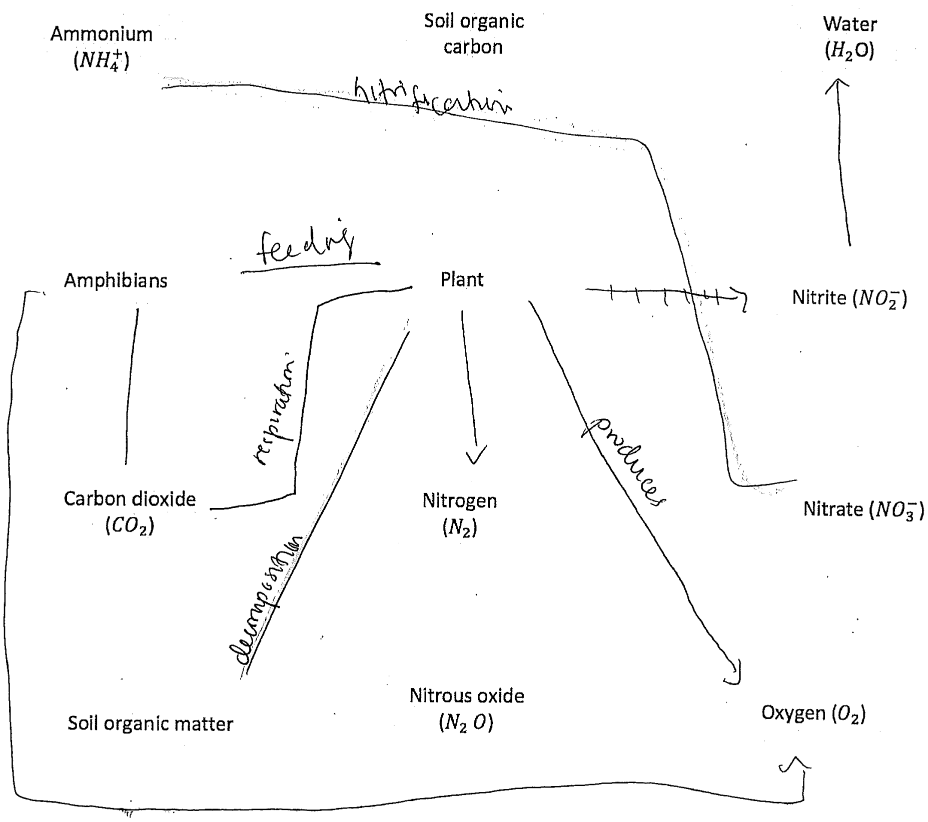
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



122(3)

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links

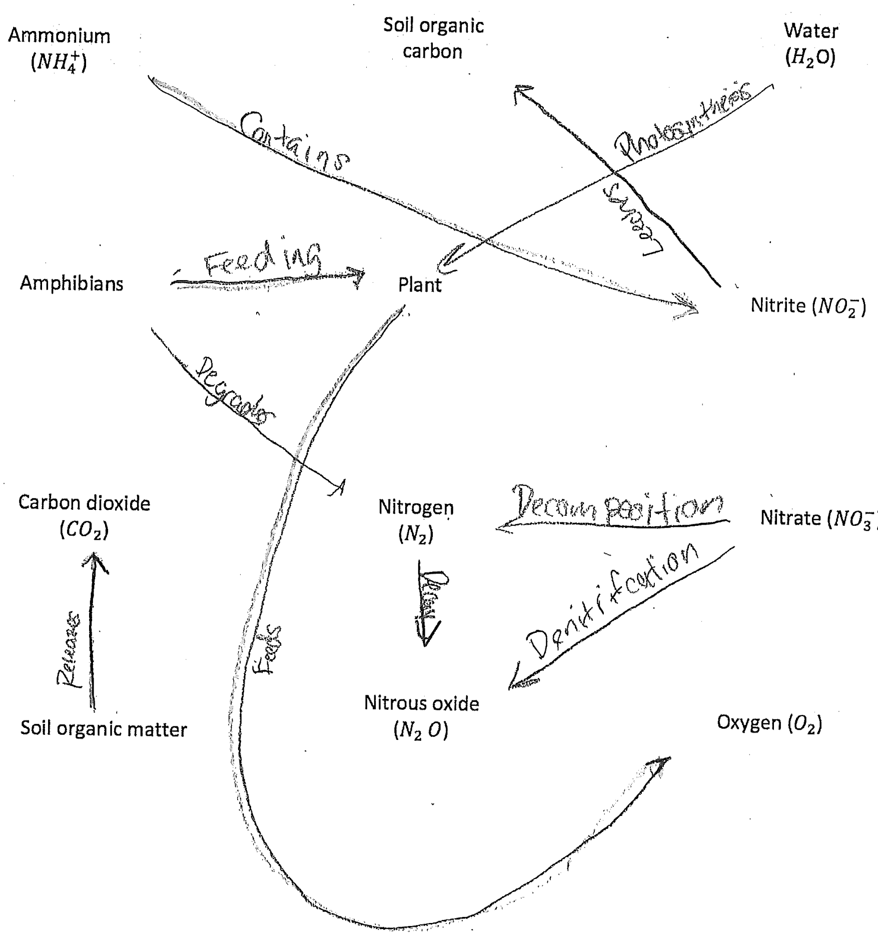


126(60).

Nan

In this concept map, you need to show your understanding of how these terms are connected.

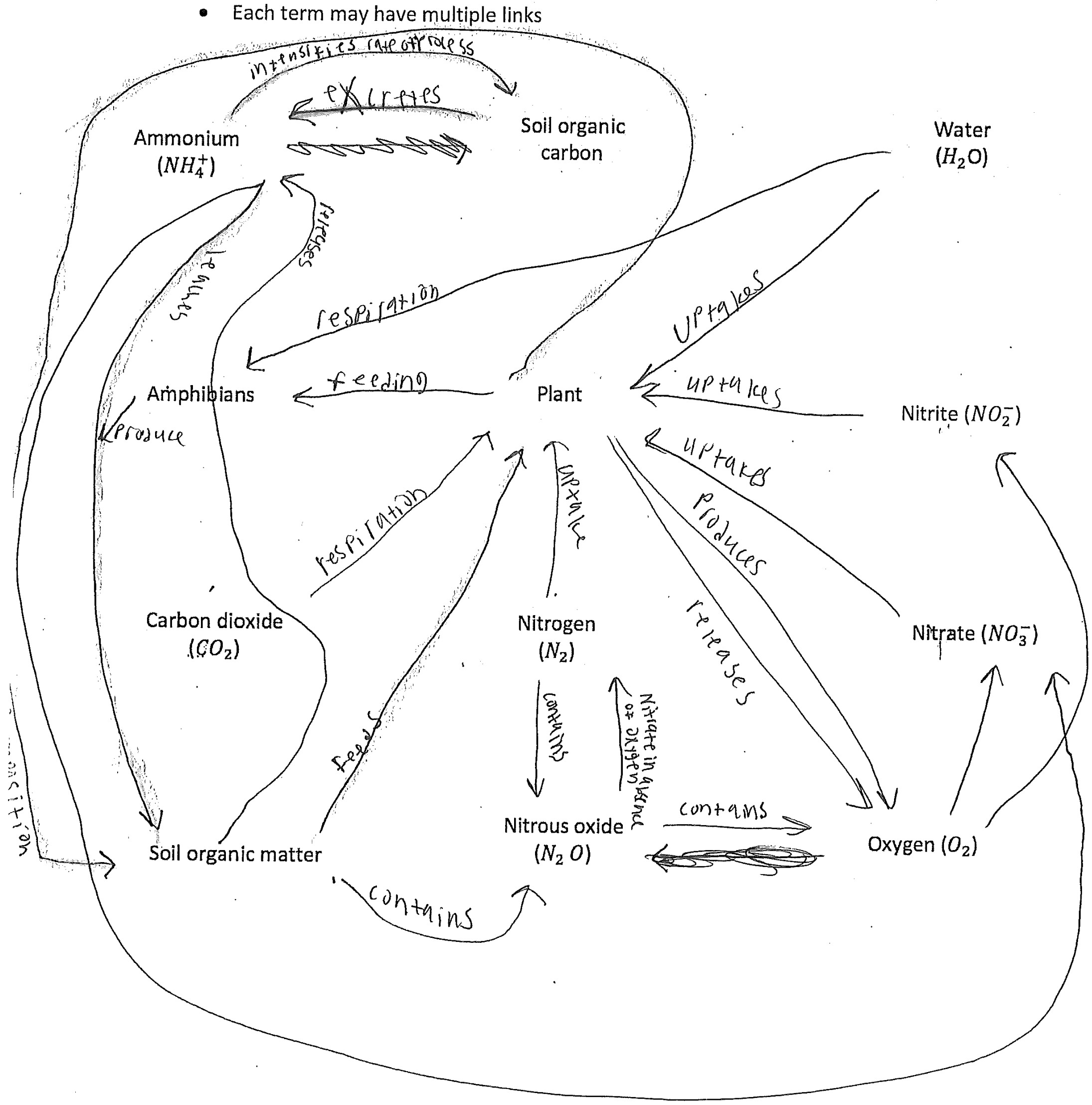
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



103(12)

In this concept map, you need to show your understanding of how these terms are connected.

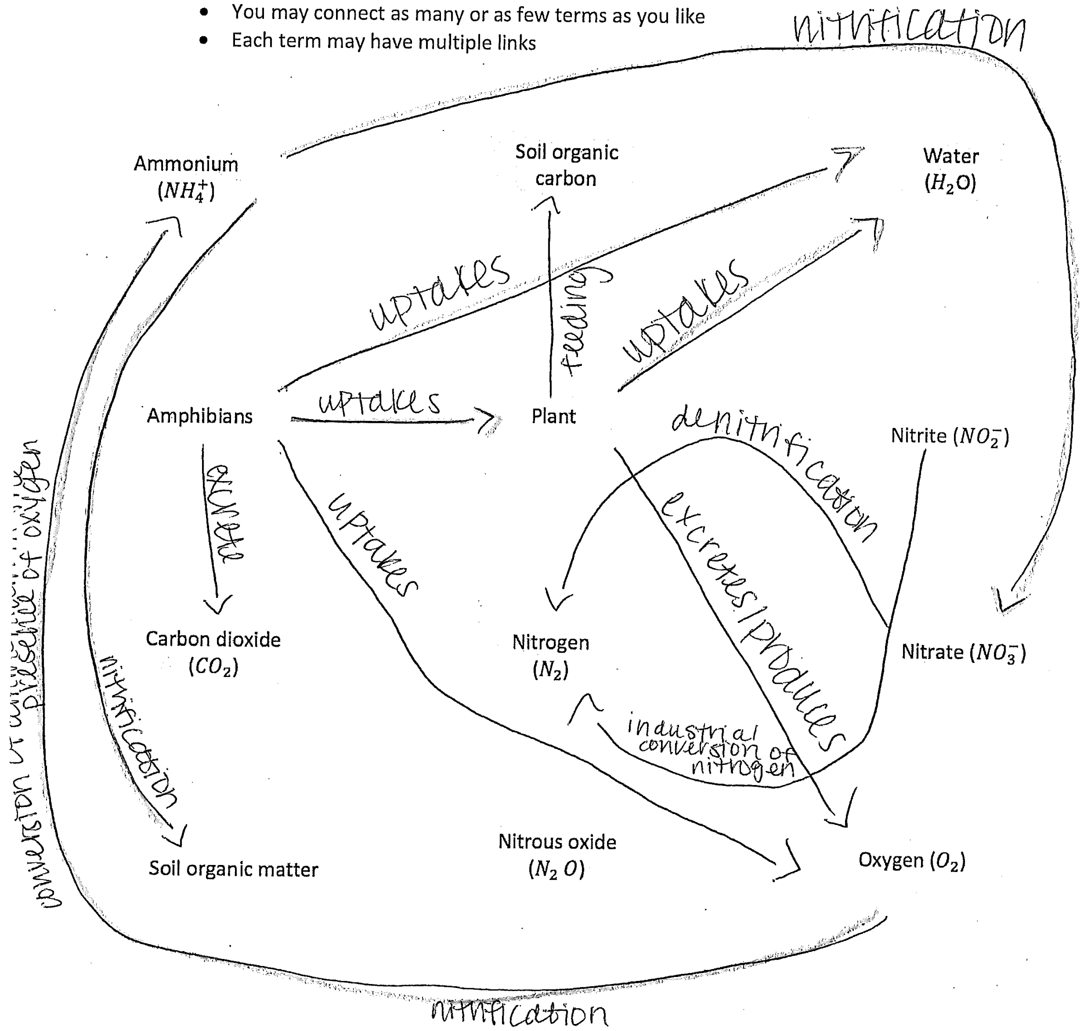
- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



119(24)

In this concept map, you need to show your understanding of how these terms are connected.

- Draw arrows to connect the terms below and to indicate the direction of the link
- You may connect as many or as few terms as you like
- Each term may have multiple links



Appendix C

Instructions for Coding Identified Connections between Objects in Concept-Maps

Appendices 1D and 2D (codebooks) contain student ID-- randomly generated three-digit number. The one or two-digit number (located in brackets next to the student ID) corresponds to pre- or post-assessment.

Categories of Terms Used in Concept Maps

Terms reflecting living and non-living entity have been defined as macro-objects: plant, amphibians and soil organic matter, and water shared by nitrogen and carbon cycles.

The rest of the terms are molecular objects. Molecular objects that belong to carbon cycle are: carbon dioxide (CO_2); oxygen (O_2); and soil organic carbon (treated as glucose macro-molecule within the curricular unit). Molecular objects that belong to nitrogen cycle are: nitrogen (N_2); nitrous oxide (N_2O); ammonium (NH_4^+); nitrate (NO_3^-); and nitrite (NO_2^-).

Initial Codes for Connections

Coded object connections dealt with single connections between two objects. Codes developed for connections that link molecules to each other were labeled as molecular connections. If both molecules were ascribed to nitrogen cycle they would be coded as nitrogen molecular (Table 1); if both molecular objects belong to carbon cycle, they were coded as carbon molecular. Connections that link molecular object to macro-object were coded based on which cycle the molecular object was ascribed to. If molecular object was ascribed to nitrogen cycle, the connection was coded as Macro-Nitrogen molecular; if molecular object was ascribed to carbon cycle, the connection was coded as Macro-Carbon molecular (Table 1). Given the age of the students in this sample (high school students), connections that interrelated exclusively macro-objects without connecting to molecular objects were excluded from the analysis. For instance, connections that linked plant to amphibian and to no other molecular object were not counted.

Table 1

Initial codes for molecular and macro-molecular connections within cycles

Codes	Definition	Example
Nitrogen-Nitrogen molecular	Links between molecular components from nitrogen cycle	N_2—NH_4^+
Carbon-Carbon molecular	Links between molecular components from carbon cycle	CO_2—O_2
Macro-Nitrogen molecular	Links between nitrogen cycle molecules and macro-objects	Plant—NH_4^+
Macro-Carbon molecular	Links between carbon cycle molecules and macro-objects	Amphibian—CO_2

Codes were developed for connections linking molecular objects that belong to two separate cycles (nitrogen and carbon cycles), relating two cycles on the molecular level and labeled as Carbon-Nitrogen molecular (Table 2

Table 2

Initial codes for connections bridging nitrogen and carbon cycles

Codes	Definition	Example
Carbon-Nitrogen-molecular	Links connecting molecular components from nitrogen and carbon cycles	O_2—NH_4^+

Determining Validity of Identified Connections

Based on descriptions, objects connections were validated for accuracy. According to Arnold & Wade (2017), one of the ways to measure validity of links is to assess identification of object connections, which relates two objects to each other in some way. Because students that were assessed are high school students that had a wide range of language levels, assessment of object connections based on students' ability to identify links that interrelate objects accounted for a wide range of reading levels. Here is the list of description phrases that were provided to students during assessment:

Excretes	Denitrification	Separation of a substance into simpler elements
Conversion of nitrate in the absence of oxygen	Lightning	Photosynthesis
Uptakes	Nitrification	Biological nitrogen fixation
Conversion of ammonium in the presence of oxygen	Releases	Denitrification
Decomposition	Leaches	Degrades
Respiration	Produces	Industrial conversion of nitrogen
Conversion of carbon dioxide into sugar	Contains	Intensifies the rate of the process
Mineralization	Feeding	Decay

Figure 1. List of description phrases

To be considered accurate, the description phrase that connected two objects could be interrelated within a specific process or could be interrelated by a process-wide level of relatedness. For instance, NH_4^+ -----NO_3^- objects can be interrelated by a specific process of nitrification. In another instance, plant---- NH_4^+ objects can be interrelated by a process-wide level of relatedness: degrade, decay, decomposition; leaches, produces, releases. Description phrases were provided in a word bank but students were not limited to those terms.

Additional remarks

1) ‘contain’ (description phrase) was not considered invalid if interrelated two molecules that contain the same chemical element (example N_2—NH_4^+ not valid if described as ‘contains’)
2) ‘feed’ (description phrase) was considered valid if interrelated to plant

Treatment of the description phrases was defined largely by how it was treated during the curriculum. Direction of the links (arrow) was not relevant for this assessment.

Appendix 1D

Initial Codes for Connections Identified and Assessed as Valid in Pre-Assessment

Student ID	Carbon-Nitorgen molecular links based on descriptions	Macro-Nitorgen molecular links correct based on decriptions	Nitrogen-Nitrogen molecular links correct based on descriptions	Macro-Carbon molecular links correct based on descriptions	Carbon-Carbon molecular links correct based on descriptions
	Pre	Pre	Pre	Pre	Pre
111 (23)	0	0	0	0	0
101 (6)	0	0	0	3	0
118 (46)	0	0	0	4	0
106 (26)	1	1	1	3	0
129 (19)	0	0	2	4	0
113 (14)	0	0	0	2	1
117 (48)	0	0	0	1	0
107 (9)	0	0	0	1	0
120 (39)	0	0	1	4	0
128 (10)	1	1	0	2	0
116 (8)	0	0	0	3	0
102 (29)	0	0	0	4	0
104 (31)	0	0	1	2	0
123 (20)	0	1	0	4	0
100 (30)	0	0	0	3	0
105 (11)	0	1	0	3	0
121 (15)	0	0	0	1	0
122 (16)	0	0	0	2	0
126 (32)	0	0	1	2	0
103 (45)	0	1	0	2	0
119 (1)	0	0	0	1	0

Appendix 2D

Initial Codes for Connections Identified and Assessed as Valid in Post-Assessment

Student ID	Carbon-Nitrogen molecular correct based Post results	Macro-Nitrogen molecular links correct based on descriptions Post	Nitrogen-Nitrogen molecular links correct based on descriptions Post	Macro-Carbon molecular links correct based on descriptions Post	Carbon-Carbon molecular links correct based on descriptions Post
111 (50)	0	0	0	4	0
101 (53)	0	2	0	4	0
118 (33)	1	1	1	2	0
106 (52)	0	0	2	2	0
129 (44)	1	3	4	3	0
113 (57)	0	0	1	3	1
117 (5)	1	4	4	5	0
107 (13)	2	0	2	3	0
120 (28)	1	1	1	2	0
128 (36)	2	2	0	1	0
116 (49)	0	4	1	3	0
102 (22)	0	1	3	4	0
104 (2)	0	1	4	5	0
123 (38)	0	2	1	5	0
100 (7)	0	3	2	3	0
105 (35)	1	1	1	2	0
121 (37)	1	4	2	5	0
122 (3)	0	0	1	2	0
126 (60)	1	1	3	2	0
103 (12)	1	4	1	2	0
119 (24)	1	1	2	4	0